VOLUME 21, 1959/60, No. 2 pp. 41-72 Published 16th December 1959

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

A WIDE-BAND TRIODE AMPLIFIER WITH AN OUTPUT OF 10 W AT 4000 Mc/s

by J. P. M. GIELES and G. ANDRIEUX *). 621.375.2.029.6:621.385.3.029.6

This article describes an amplifier developed for use with the microwave disc-seal triode EC 59, dealt with earlier in this journal. The article follows upon an earlier one concerning an amplifier for the EC 157 triode, designed for lower outputs.

The disc-seal triode type EC 59 was developed for use in microwave radio links in which the power delivered by the EC 157 is inadequate [1]). In view of its higher output, and also because of some constructional differences between the two tubes, the EC 59 cannot be used in the amplifier designed for the EC 157 [2]). This article describes the construction and properties of an amplifier specially developed for use with the EC 59. Since both amplifiers obviously resemble each other in many respects, we shall make frequent reference to the earlier article [2]), denoted here as I.

Principal differences between the triodes EC 59 and EC 157

Fig. 1 shows the above two tubes side by side. The chief difference between them is that the EC 59 can deliver a power of more than 10 W, whilst the output of the EC 157 is only 1.5 W. For this reason the anode of the EC 59 is *water-cooled,* and this called for a radical modification in the design of the amplifier. Another important difference between the two tubes is the size of the cathode holder. In the EC 59 its length has been reduced and its diameter increased. This entailed a different construction in order to match the tube properly to the waveguide.

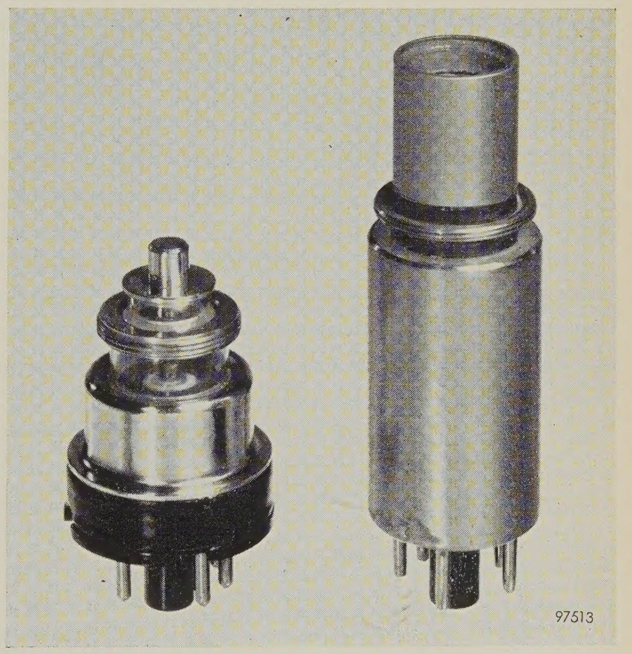


Fig. 1. Disc-seal triodes EC 157 (air-cooled) and EC 59 (water-cooled), both for 4000 Mc/s.

The input circuit

Fig. 2 shows an equivalent circuit for the input impedance of a disc-seal triode (see also fig. 3 in I). R_{gk} is the input resistance measured directly between grid and cathode, C_{gk} the capacitance between these electrodes and L_k the inductance of the cathode base, the cathode bush and the cathode disc. Parallel with this is the capacitance C_d between grid disc and cathode disc. In the two tubes EC 157 and EC 59, R_{gk} is about 60 Ω and C_{gk} about 1.6 pF.

*) Laboratoires d'Electronique et de Physique appliquée, Paris.

1) V. V. Schwab and J. G. van Wijngaarden, The EC 59, a transmitting triode with 10 W output at 4000 Mc/s, Philips tech. Rev. **20**, 225-233, 1958/59 (No. 8). In some earlier publications the EC 59 is referred to as 49 AF. — The tube EC 157 differs from the older type EC 57 in that its cathode has a longer life.

2) J. P. M. Gieles, A 4000 Mc/s wide-band amplifier using a disc-seal triode, Philips tech. Rev. **19**, 145-156, 1957/58; referred to henceforth as I.

The value of L_k in the EC 157, however, is approximately 3×10^{-9} H, whereas in the EC 59 it is only 10^{-9} H. If we now replace the input impedance of the tubes by a resistance and a reactance in parallel,

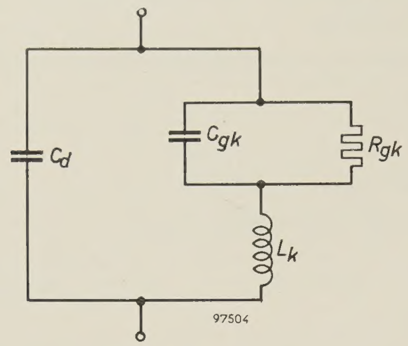


Fig. 2. Equivalent circuit for the input of a disc-seal triode. R_{gk} input resistance between grid and cathode; C_{gk} capacitance between these electrodes; L_k inductance of cathode holder and cathode bush; C_d capacitance between grid disc and cathode bush.

this resistance will be about 400 Ω in the case of the EC 157 at 4000 Mc/s, which roughly corresponds to the characteristic impedance of the waveguide. With the EC 59, on the other hand, this resistance is a mere 10 Ω. This makes it necessary to introduce an impedance transformer between the input waveguide and the tube.

For this purpose a quarter-wavelength transformer can be used. If this is made of a normal rectangular waveguide, however, the frequency band in which good matching is possible is found to be fairly narrow. A simple method of reducing this frequency-dependence is to use a ridge waveguide [3])

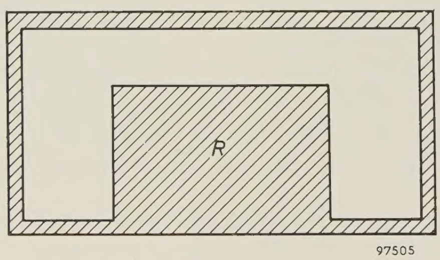


Fig. 3. Transversal section through a waveguide with ridge R, as used for the quarter-wavelength transformer for matching the input impedance of the tube to the characteristic impedance of the input waveguide.

having a transversal section as shown in *fig. 3*. Externally the dimensions are the same as those of the ordinary waveguide. The ridge considerably reduces the characteristic impedance of the waveguide, giving it properties resembling those of a parallel-wire transmission line. When a short section of waveguide (about $\frac{1}{4}\lambda$) in front of the cathode is provided with such a ridge of appropriate dimensions, good matching can be achieved in a frequency band almost twice as wide as when a normal quarter-wavelength transformer is used. The construction is illustrated in *fig. 4*. The tube is inserted from underneath and, the grid disc being threaded, screwed into the upper side of the waveguide. The cathode is connected to the lower side of the waveguide (in this case the top of the ridge) by means of a choke coupling (see I). The standing-wave ratio in the input waveguide of the amplifier equipped with an average tube is shown in *fig. 5* as a function of frequency (curve a). This curve is found when the anode circuit is detuned with respect to the reference frequencies so as to eliminate its effect on the input impedance of the tube.

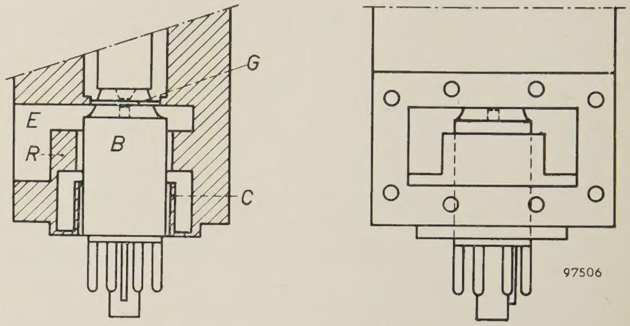


Fig. 4. Simplified representation of the input section of the amplifier. E input waveguide; B cathode bush; R ridge; C choke coupling; G grid disc.

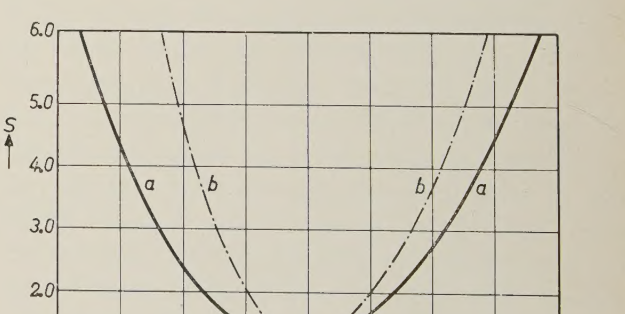


Fig. 5. Standing-wave ratio s in the input waveguide as a function of frequency f. Curve a applies before the reactive elements for matching the tube to the waveguide have been introduced. Curve b applies after their introduction, the tube being matched to the waveguide at 4000 Mc/s. In both cases the anode circuit is detuned with respect to the reference frequency.

[3]) See e.g. G. C. Southworth, Principles and applications of waveguide transmission, Van Nostrand, New York, 1950, p. 134 et seq., and S. B. Cohn, Properties of ridge waveguides, Proc. Inst. Rad. Engrs. **35**, 783-788, 1947.

If we take the bandwidth to mean the difference between the frequencies at which the load resistance of the waveguide receives half the maximum power, a simple calculation shows that this bandwidth is equal to the difference of the frequencies at which the standing-wave ratio is $3 + 2\sqrt{2} = 5.8$. From fig. 5 we accordingly find a bandwidth of 700 Mc/s.

In order to be able to match individual tubes accurately to the waveguide at any desired frequency in the band to be covered, two variable reactive elements are introduced into the waveguide as in I. The first is located near the beginning of the ridge, and the second at about an eighth of a wavelength before the ridge. These elements are not shown in fig. 4; they can, however, be seen in the photograph of the complete amplifier in *fig. 6*.

In fig. 5, curve *b* represents the standing-wave ratio in the input waveguide when the above matching elements are fitted and when the tube (again with detuned anode circuit) is matched to the input waveguide at a frequency of 4000 Mc/s. We see that the introduction of the matching elements has reduced the bandwidth to about 500 Mc/s.

When the tube is switched off the input impedance is obviously different and the tube is no longer matched to the waveguide. In this case the standing-wave ratio in the input waveguide is much larger, being about 20 [4]).

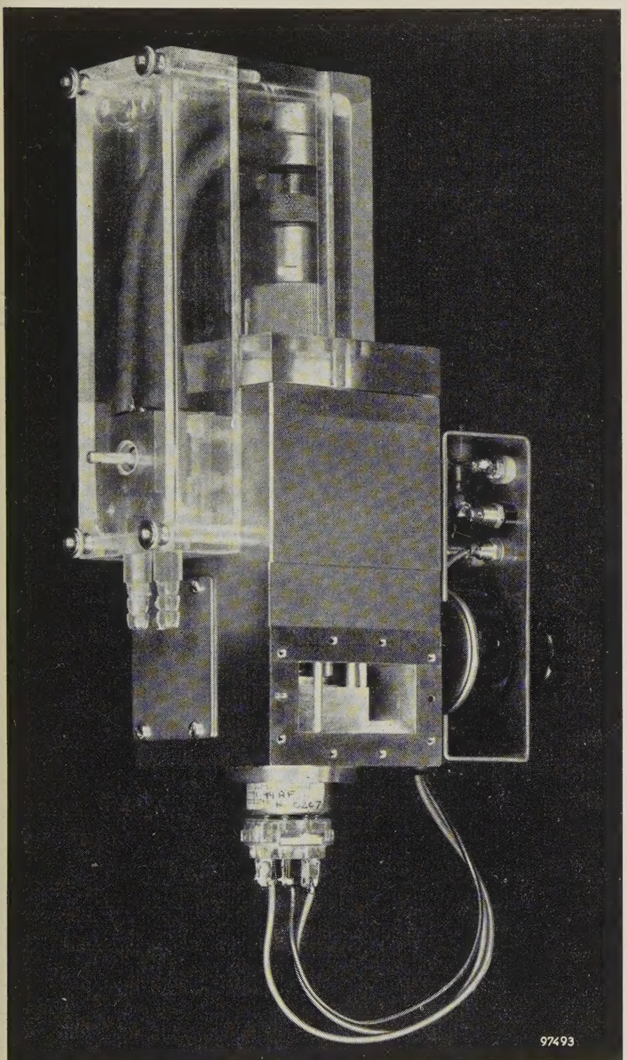


Fig. 6. Amplifier with EC 59 triode, seen from the input side. The safety cover on the left contains, among other things, the anti-corrosion block. In the input waveguide the two reactive elements for matching the tube to the waveguide can be seen.

The output circuit

As in the amplifier for the EC 157, the anode of the tube is contained in a resonant cavity which is terminated at the top by a plunger. The anode is again provided with an extension piece constituting the inner conductor of a coaxial transmission system. The first section of this system, i.e. the part inside the plunger, acts as a quarter-wavelength transformer. The high-frequency energy passes between the plunger and this inner conductor, and arrives in the second section of the coaxial line. This line must be properly matched to the output waveguide. The design of the transition from this line to the output waveguide is complicated in this case by the fact that the inner conductor, the lower end of which is joined to the anode of the tube, has to contain the tubes for supplying and removing the cooling water. This makes it necessary that the inner conductor should reach the opposite wall of the waveguide, so that a probe-construction as in the EC 157 amplifier is not possible. If the inner conductor makes high-frequency contact with the opposite wall of the waveguide, the characteristic impedances of coaxial line and waveguide must be equal. The characteristic impedance of the waveguide is approximately 500 Ω, but of the coaxial line only about 20 Ω, the reason being that the dimensions of the coaxial line are governed by those of the tube and resonant cavity. Here too, therefore, impedance transformation is needed. The use of a single quarter-wavelength transformer was not sufficient in this case, since the frequency range in which a matched transition is possible is too small. It was found that a transition from coaxial line to waveguide requiring no means of correction in the entire frequency band from 3800 to 4200 Mc/s could be achieved with two quarter-wavelength transformers, one in the coaxial line and the other in the waveguide.

4) This confirms that the input impedance of the tube is closely dependent on the transconductance, and is not caused, for example, by losses in the materials.

This is illustrated in *fig. 7*. The standing-wave ratio of this transition is smaller than 1.2 within the frequency band mentioned, and the space inside the narrowed section of the inner conductor is sufficient to accommodate cooling-water tubes.

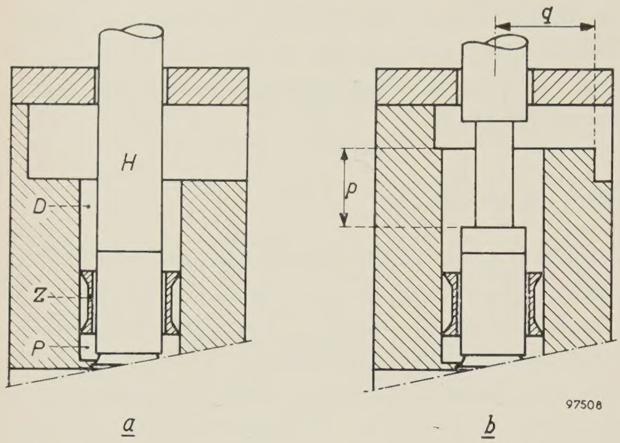


Fig. 7. Simplified representation of the output section of the amplifier, *a*) without quarter-wavelength transformers, *b*) with two quarter-wavelength transformers, one being included in the coaxial output line and the other in the output waveguide. *D* cylindrical hole constituting, together with the inner conductor *H*, the coaxial output line. *Z* plunger for tuning the anode resonant cavity *P*. The distances denoted by *p* and *q* are approximately a quarter wavelength.

The upper part of the inner conductor must make high-frequency contact with the waveguide and nevertheless be insulated from it for direct voltage. This is again achieved with a choke coupling. In view of the high voltage (500 V) and the narrow gap (0.5 mm) it is important that the inner conductor be very accurately centred. Since it is screwed to the anode, and the tube is fixed with respect to the amplifier block by the grid disc, only slight eccentricity of the anode would be enough to cause a short-circuit. For this reason a flexible section is incorporated in the inner conductor at the position where the constriction begins (denoted by *B* in fig. 8). The wall thickness of the horizontal face at that point is only 0.3 mm, making it possible to move the upper part slightly with respect to the lower, and thus to centre the upper part with respect to the amplifier block. If this were done automatically when screwing-in the tube, there would be a risk of damaging the grid screw thread. The construction is therefore such that the tube, fitted with the inner conducter, is first freely screwed in, after which a centering cap is attached to the lid. This cap is also utilized for leading-in the high tension. As a safety precaution the cap is completely surrounded by an insulating cover (see fig. 6).

The amplifier, as hitherto described, will show a frequency characteristic with a single peak and have a bandwidth of 100 Mc/s. As in the case of the amplifier using the EC 157, however, we require here too a bandpass-filter curve with transitional coupling. If a second resonant circuit is introduced in the output waveguide for this purpose (an "iris", see I), it must be so positioned that the system between the top of the plunger and the iris is electrically equivalent to an uneven number of quarter wavelengths. In the amplifier for the EC 157 this distance was equivalent to a line one quarter wavelength long. Owing to the two quarter-wavelength transformers required in the output circuit for the EC 59, this distance could not be maintained. The distance between the iris and the top of the plunger in this case therefore had to be electrically equivalent to three quarter-wavelengths. It was found, however, that with one fixed place for this iris it was no longer possible to satisfy the above-mentioned condition with sufficient accurary for all frequencies in the range from 3800 to 4200 Mc/s. For this reason the iris for the EC 59 is not mounted in the amplifier, but screwed to the output flange as a separate unit. The frequency band to be covered is now divided into two parts, one from 3800 to 4000 Mc/s and the other from 4000 to 4200 Mc/s. For each part a separate unit is used, having a different effective iris-to-plunger distance. Each unit also contains a screw used for adjusting the coupling to the required value (see I).

When the anode circuit is now tuned and adjusted to constitute a band-pass filter with transitional coupling, the bandwidth between the points where the gain has dropped 0.1 dB with respect to the gain at the central frequency is found to be 55 Mc/s, as in the case of the EC 157 amplifier. Since the signals to be transmitted cover a frequency band of 20 Mc/s, this is more than adequate.

The cooling system

The anode of the EC 59 dissipates 125 W (500 V, 250 mA). This power is developed on the anode surface, the area of which is about 12 mm². In order to keep heat generation on the surface within reasonable bounds, water cooling is employed. Since a power of 300 W can be continuously dissipated by a stream of water of 0.5 litres per minute, this rate of flow is amply sufficient.

The anode is hollow and internally threaded. The inner conductor of the coaxial output system, is screwed into the anode and is provided with a bore intended for carrying off the cooling water, which is introduced through a thin pipe passing centrally through the bore and terminating just

above the actual anode surface. A sketch of the arrangement is shown in *fig. 8*. A watertight seal is provided by a rubber ring. The contact between the metal parts is external, so that the rubber ring does not affect the electrical performance.

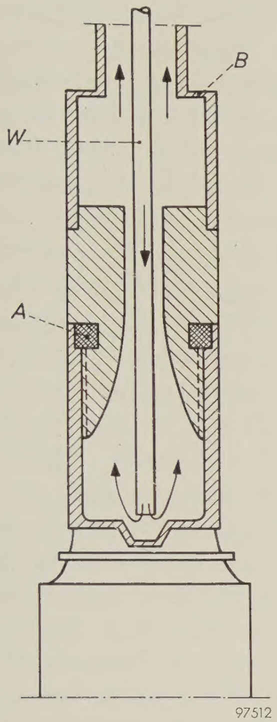


Fig. 8. Simplified cross-section of the inner conductor of the coaxial output line. W feed pipe for cooling water; B flexible portion to allow centering in the block; A rubber ring. The arrows indicate the water flow.

After the tube has been introduced into the amplifier block, a special union which converts the coaxial water supply into a twin-duct system is fitted to the top of the inner conductor. The supply duct and the outflow duct pass an insulated metal block attached to the side of the amplifier and kept at the same potential as the anode. The idea underlying this anti-corrosion block, as it is termed, is the following. The cooling water always contains impurities (even in a closed water-circuit), which give rise to electrolysis and hence to corrosion. The process is accelerated by the fact that the anode material corrodes easily and is difficult to provide with a protective plating. Since the first portion of the part under high tension is the most severely attacked, the water is first conducted through the metal block mentioned and then to the amplifier proper. As a result, this block corrodes first, and can later be replaced, whilst the amplifier itself is not affected. Since the anti-corrosion block is under high tension, it is also included under the safety cover (see fig. 6).

Properties of the complete amplifier

Small signals

The gain obtained with most of the tubes tested is about 10 dB in the case of small signals at a bandwidth of 100 Mc/s. If, after adjusting the anode circuit as described above, we again measure the standing-wave ratio in the input waveguide, we find it to be approximately 1.5 at the central frequency. Here, then, the feedback is less than with the EC 157, for which the corresponding value is about 2. The reason is to be found in the entirely different configuration in the effective triode section. The frequency at which no internal feedback occurs is about 5200 Mc/s with the EC 157, whereas with the EC 59 it lies in the region of 4200 Mc/s. This is much closer to the operating frequency, which explains the smaller feedback.

Strong signals

Fig. 9 shows a plot of the gain versus output power. The curve represents the average of measurements made on 16 tubes. The anode voltage was 500 V and the anode current 250 mA. The amplifier was again adjusted for a small-signal bandwidth of 100 Mc/s, at which the gain was almost 10 dB. At an output of 10 W the average gain was 8.6 dB [5]). The gain was still found to be more than 6.5 dB at an output power of 20 W, which would call for an input power of 4 W. If a tube is to be loaded continuously with such a high input power, however, measures must be taken to prevent overloading of the grid. It has been found that the maximum possible driving power is approximately reached at a grid current of 15 mA. This grid current depends among other

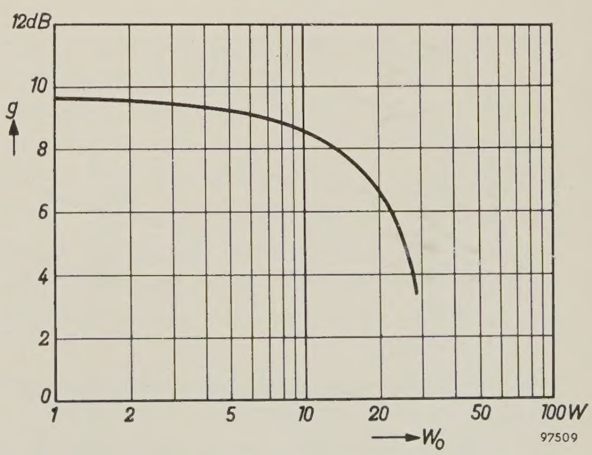


Fig. 9. Gain g as a function of power output W_0 of the EC 59 amplifier. Bandwidth of the amplifier 100 Mc/s. Anode voltage 500 V, anode current 250 mA.

---

[5]) The guaranteed value is 7 dB.

things on the static I_a-V_g characteristic of the tube and thus differs from tube to tube. With most tubes we were able to produce an output of 15 W without exceeding this limit. The gain was then 7 dB and the input power 3 W [6]). If a higher output is required, it can be achieved by increasing the anode voltage whilst keeping the anode current constant. This has little effect on the curve in fig. 9, but the negative grid voltage is now higher with the same anode current. The grid current therefore drops, thus permitting a higher driving power.

The driving power for the EC 59 can be obtained in various ways. One way is to use an EC 157 for the purpose. This delivers 1.5 W, which is amplified by the EC 59 to more than 10 W. One can also use two EC 157 amplifiers connected in parallel, which can readily be done with microwave triode amplifiers by means of power dividers in the waveguides. In this way twice the power is produced for the same gain, so that with two EC 157 tubes an output of 3 W can be obtained. This is amplified by an EC 59 amplifier to 15 W.

If an even higher power output is required, there is the further possibility of connecting two EC 59 amplifiers in parallel. With two parallel EC 157 amplifiers as the driving stage, an output of more than 20 W can be achieved. Driving the double output stage with a single EC 59, in its turn driven by an EC 157, can give 30 W without the maximum permissible grid current being exceeded.

In all these circuits the cascaded amplifier stages should be coupled by means of directional isolators. As explained in I, this considerably reduces many difficulties arising from feedback.

Group delay, AM-PM conversion

In the foregoing we have discussed the properties of the amplifier only with regard to the amplitude of the signals. In radio links using frequency-modulation it is also important, however, to examine the phase shift between the input and output signals. We can measure this phase shift φ as a function of frequency and as a function of the output signal; from the first-mentioned relation we can calculate the group delay, $\mathrm{d}\varphi/\mathrm{d}\omega$. We can also measure the group delay directly.

Extensive group-delay measurements were carried out at the time on the EC 157 amplifier [7]). One of the conclusions was that the group delay of a triode amplifier is determined almost entirely by the circuit employed, and is not noticeably affected by the tube or the signal level. Since it could safely be assumed that this would also apply to the EC 59 amplifier, which after all has the same bandwidth, no group-delay measurements were carried out in this case. The group delays, including the variations in group delay within the frequency band of the transmitted signals, are expected to be the same as those occurring in the EC 157 amplifier.

The situation is different, however, when we turn from the group delay $\mathrm{d}\varphi/\mathrm{d}\omega$ to the phase shift φ, for this does depend on the signal level. Since we are concerned here with frequency modulation, all the signals involved might be assumed to have a constant amplitude, in which case the above consideration would be of no importance. In practice, however, a constant signal level is seldom possible. As a rule there is also some slight amplitude modulation of the input signal, giving rise to a phase variation which, in frequency modulation, causes distortion. This AM-PM conversion, as it is termed, is expressed in degrees of phase variation of the output voltage resulting from a 1 dB variation of the input signal. The AM-PM conversion was measured on the EC 59 as a function of the output power. It was found to amount to 1.2° per dB at a power of 15 W. Compared with other microwave tubes, this is a particularly low value. With two amplifiers in parallel the AM-PM conversion remains the same, making it possible to obtain an output of 30 W with an AM-PM conversion of only 1.2° per dB.

[6]) Since sufficient life-tests have not yet been carried out at this power, users are recommended to keep the input power of the tube lower than 2 W for practical purposes.

[7]) See article I and also: J. P. M. Gieles, The measurement of group delay in triode amplifiers at 4000 Mc/s, L'Onde électrique **37**, 781-788, 1957.

Summary. An amplifier designed for use with the disc-seal triode EC 59 is described. The amplifier, which operates in the frequency band from 3800 to 4200 Mc/s, was evolved from an earlier-described type built for the EC 157 triode. Differences in the construction of the two tubes called for considerable modifications both at the input and output side of the amplifier block. The need for water cooling of the anode also involved constructional changes. Corrosion of the tube or amplifier block is prevented by conducting the cooling water through a detachable metal block kept at the same potential as the anode. At an output of 10 W and a bandwidth of 100 Mc/s the average gain measured on a series of tubes was 8.6 dB. An output of 15 W is obtainable without overloading the grid. If higher outputs are required, two EC 59 amplifiers can be connected in parallel.

As with the EC 157 amplifier, the group-delay variations in the frequency band concerned are deduced to be very small. Phase variations due to changes in the amplitude of the signal are also very small, being about 1.2° per dB.

EXPERIMENTS IN THE FIELD OF PARAMETRIC AMPLIFICATION

621.375.9

In many laboratories a great deal of work is now being put into developing the theory and practice of parametric amplification. The principle of this method of amplification is by no means new, but having long lain dormant it has come into prominence only in recent years as a result of research on the low-noise amplification of very weak signals as occur, for example, in radio astronomy and man-made satellite communications. In amplifiers equipped with the more or less traditional thermionic valves a fundamental limit is set to the reduction of the noise level by the random fluctuations of the electron emission from the hot cathode, and in amplifiers equipped with transistors by the statistical nature of the diffusion and recombination of charge carriers, which in this case determine the amplification. Such effects do not necessarily enter into parametric amplification, which is based on the periodic variation of one parameter of an oscillatory system, e.g. the stiffness in a mechanical system or the capacitance in an electrical circuit. In principle it should be possible with this method of amplification to achieve an extremely low noise level [1]).

Although numerous theoretical studies have been published on the mechanism of parametric amplification, and it has also been successfully applied in practice, it cannot be said that its operation is understood and under control to the same extent as the operation of amplifiers fitted with valves and transistors. For example, it is not yet possible to produce an optimum design for a parametric amplifier required to operate with a given frequency characteristic (or bandwidth). The interpretation of experiments in this field is often made more difficult by the absence of exactly defined conditions, so that various effects have to be dealt with that cannot be distinguished from each other.

Our own work on this subject has led to the construction of a simple experimental arrangement which permits the accurate testing of certain fundamental ideas and with which further experiments can be made. In this article we shall briefly describe this arrangement and some results of experiments. First of all, however, we shall explain summarily the principle of parametric amplification.

If a taut, slightly elastic string be pulled lengthwise at the appropriate frequency, the string will enter spontaneously into transverse vibration with a frequency equal to half that at which it is pulled (Melde's experiment, *fig. 1*). An LC resonant circuit in which the capacitance is periodically varied may be regarded as the electrical analogue of this

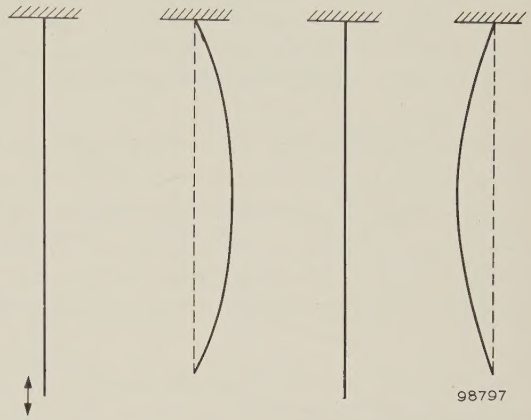


Fig. 1. When an elastic string is periodically pulled lengthwise with a frequency F, the string enters spontaneously into transverse vibration at its resonance frequency f, provided that $F = 2f$ (Melde's experiment, Ann. Physik u. Chemie **109**, 193, 1860).

long familiar phenomenon. Let us suppose that we have a parallel-plate capacitor, the distance between the plates being d_0, and that an alternating current flows through the (resistanceless) circuit at the resonant frequency $f = 1/(2\pi\sqrt{LC})$. The charge on the capacitor, and hence the voltage, varies sinusoidally with time. We now pull the two plates of the capacitor abruptly apart to a distance $d_0 + \delta$ (*fig. 2*) at the moment when the charge and thus

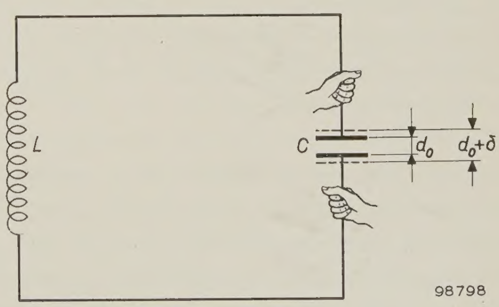


Fig. 2. LC resonant circuit in which the plates of the capacitor are pulled apart and pushed back again at certain moments.

the voltage of the capacitor reaches a maximum — irrespective of which of the plates is positive — and we push the plates back to their original position at the moments when the plates are uncharged and

[1]) As far as we know this was first suggested by A. van der Ziel, J. appl. Phys. **19**, 999, 1948. Electrical circuits with varying parameters were dealt with by B. van der Pol, Experimental Wireless **3**, 338, 1926.

there is thus no voltage difference between them. The first action requires work, the second produces no work, and so energy is periodically supplied to the circuit. The result is that the amplitude of the alternating voltage increases, i.e. "negative damping" occurs. The process is further elucidated in *fig. 3*. Even though no current flows at the start, a

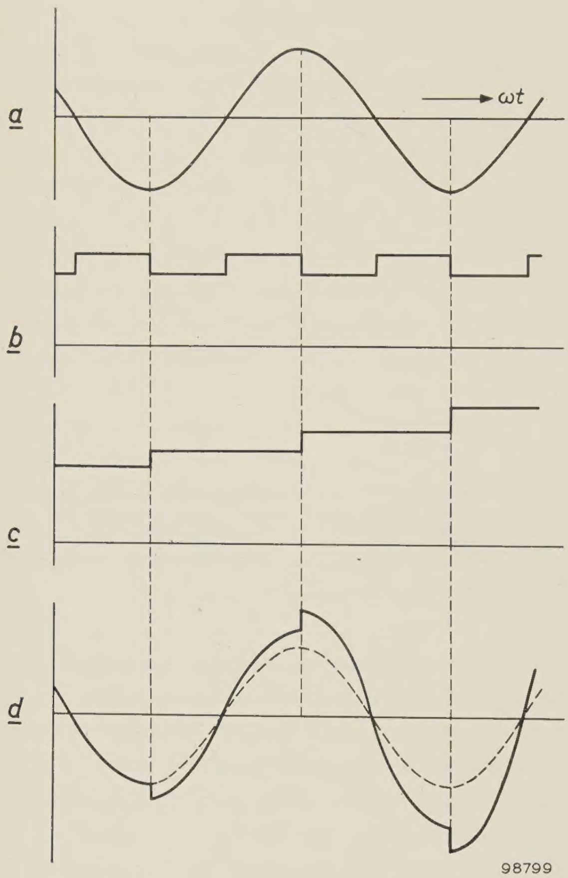


Fig. 3. Mechanism of parametric amplification in the circuit of fig. 2. In the initial state a small alternating current flows in the (resistanceless) circuit. The charge and voltage on the capacitor then vary sinusoidally with time (*a*). The capacitor plates are now displaced at certain moments so as to vary the capacitance as shown by the square wave form in (*b*). This "pumping" causes a stepwise increase of the energy in the circuit (*c*), and also of the amplitude of the voltage on the capacitor (curve *d*).

minute disturbance of equilibrium in the form of an extremely small charge — which is always present — is sufficient to initiate the process, and this causes the *LC* circuit to enter spontaneously into electrical oscillation. The frequency at which the capacitance is varied (by moving the plates back and forth), called the *pump frequency*, is most favourable when it is twice the resonance frequency of the circuit — just as in the mechanical case.

The negative damping of a circuit, which may be regarded as an effect arising from a negative resistance, implies the possibility of using it to amplify a given input signal. In this respect, however, the situation is not so simple, for one thing because of the frequency condition just referred to. The difficulty is made clear by the following consideration. For negatively damping an oscillation it is not necessary that the pumping should be exactly in phase with the oscillation (*fig. 4*). The net energy supply from the pump falls, however, as the phase angle φ increases. The supply drops to zero at $\varphi = 45°$, and becomes negative at phase angles larger than this; in other words, the oscillation is then damped instead of amplified. The damping is greatest at $\varphi = 90°$. Now if half the pump frequency (i.e. the resonance frequency f of the circuit) differs slightly from the frequency of the input signal, this is equivalent to a continuous change of phase; the oscillation is thus alternately amplified and (though to a lesser degree) damped; in other words, it is modulated in amplitude.

In attempts to arrive at a practical means of parametrically amplifying radio signals, where the aim is to achieve useful amplification in a reasonably wide frequency band, the difficulty described has been circumvented by the use of more complicated

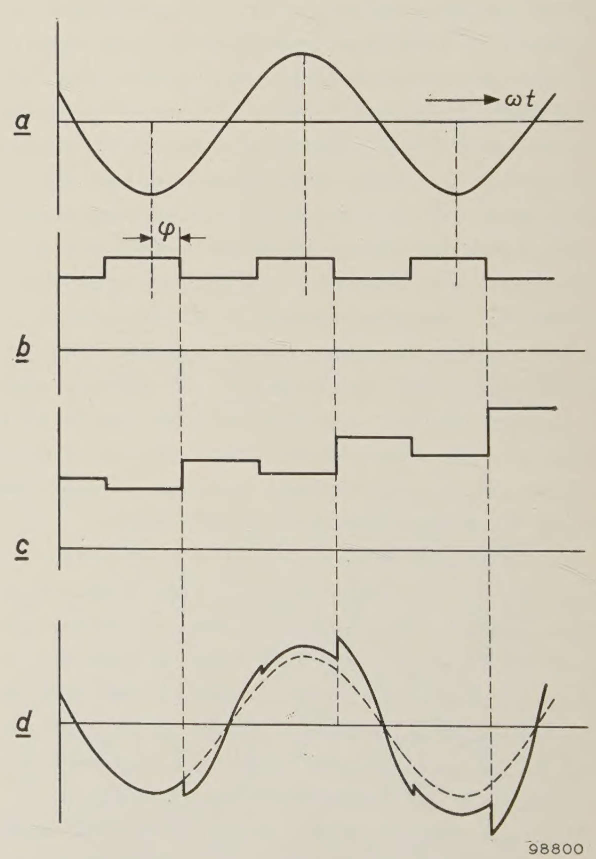


Fig. 4. If the capacitance variation (*b*) is not in phase with the alternation of the charge on the capacitor (*a*), but differs by a phase angle φ, the energy in the circuit alternately rises a step and drops a step (*c*). The steps up are greater than the steps down when $0 < \varphi < 45°$ or $135° < \varphi < 180°$. The capacitor voltage thus increases (*d*); at $45° < \varphi < 135°$ it decreases.

circuits with two or more resonance frequencies [2]). Another question concerns the method of carrying out the pumping process. The abrupt capacitance variation, effected by moving the plates to and fro by hand as in fig. 2, is obviously not intended for practical purposes. But any other mechanical variation of an oscillatory-circuit parameter is equally unpracticable because of the excessive acceleration forces involved at the very high frequencies with which we are concerned. In the attempts above mentioned, the variation is therefore effected by means of *voltage-dependent capacitances* or current-dependent inductances. An example of a voltage-dependent capacitance is the germanium diode, which can be used in the centimetric wave range. Its capacitance depends on the negative bias. If we superimpose on this an alternating voltage (the pump or control voltage), we then have a periodically varying capacitance. Parametric amplifiers have already been built in this way, and are reported to possess, as predicted, favourable noise properties [3]). These systems, however, are difficult to deal with theoretically, for the capacitance of the diode depends not only on the pump voltage but also on the oscillatory-circuit voltage to be amplified. (A further complication is the non-linear relation between capacitance and voltage.) Such systems are called *autoparametric* as opposed to *heteroparametric* systems (as in fig. 2), in which the parameter to be varied is influenced only by the pump, and does not react noticeably on the pump. If a current-dependent inductance is used, e.g. a coil or resonant cavity having an iron or ferroxcube core which is alternately saturated by a pump current (essentially a "magnetic amplifier" long used for low frequencies), this, too, is an autoparametric system, since the circuit current itself likewise contributes to the saturation.

Referring to fig. 2, if the plate distance varies according to $d = d_0 + \delta \cos 2\omega t$, i.e. the capacitance according to

$$C = \frac{C_0}{1 + \dfrac{\delta}{d_0} \cos 2\omega t}, \quad \ldots\ldots \quad (1)$$

then the charge q of the capacitor in this heteroparametric system is given by Mathieu's equation (linear second-order differential equation with time-dependent coefficients):

$$\frac{d^2 q}{dt^2} + \frac{1}{LC_0}\left(1 + \frac{\delta}{d_0} \cos 2\omega t\right) q = 0 . \quad \ldots . \quad (2)$$

The solutions of this equation, one of them with the angular frequency $\omega = 1/\sqrt{LC_0}$ (i.e. half the pumping frequency), are known and their properties have been extensively investigated [4]). They can thus be manipulated, even though the treatment is not simple.

In autoparametric systems, on the other hand, the differential equations involved are non-linear, and in general cannot be solved exactly but only by methods of approximation. It is then very difficult if not impossible to obtain any general idea of the properties of the solutions.

Thus, although practice points in the direction of autoparametric systems, it is nevertheless desirable for the purposes of fundamental research to confine oneself in the first place to the heteroparametric systems, such as the mechanically variable capacitor, which lend themselves more readily to theoretical treatment.

In the thirties attempts had already been made to vary the capacitance mechanically by using a motor-driven rotating capacitor as the pump [5]). It was in fact possible in this way to demonstrate the spontaneous onset of oscillations in an LC circuit, having a resonance frequency of 28 kc/s.

The experimental arrangement which we have devised is of a similar kind, but the capacitance variation is effected by a more manageable element, namely a magnetostrictive resonator, which also offers more possibilities for further experiments. The pump consists of a window-frame core, shown in *fig. 5*, of a suitable type of ferroxcube, widely used nowadays for ultrasonic oscillators [6]). This core is centrally clamped and is brought into longitudinal vibration by means of a winding connected to an ultrasonic generator of frequency 22 kc/s. To each of the two parallel-ground end faces a metal plate of 30×80 mm is attached. Opposite each plate, at a spacing $d_0 = 80\ \mu$, a parallel, fixed electrode is mounted. The two moving plates are electrically interconnected and constitute one plate of a capacitor, whilst the fixed electrodes, also interconnected, constitute the other plate. As can easily be calculated, the total capacitance amounts to 532 pF. To obtain an oscillatory circuit having a resonance frequency $\omega/2\pi$ of 11 kc/s (i.e. half the pump

[2]) The phase-dependence of the negative damping is usefully exploited in the "Parametron" introduced by Japanese investigators. In this device the two states of either oscillating or not are used for registering one bit of information, in a manner similar to the use of the two states of magnetization of a ferrite core.

[3]) A. Uhlir, Junction-diode amplifiers, Scientific American **200**, No. 6, 118 et seq., June 1959. — A review of parametric amplification, together with an extensive bibiography, can be found in H. Heffner, Solid-state microwave amplifiers, Inst. Rad. Engrs. Trans. **MTT-7**, 83-91, 1959 (No. 1).

[4]) See e.g. E. T. Whittaker and G. N. Watson, A course of modern analysis, Cambridge University Press, London 1920, third edition, Chapter 19, § 19.7.

[5]) L. Mandelstam, N. Papalexi, A. Andronov, S. Chaikin and A. Witt, Exposé des recherches récentes sur les oscillations non linéaires, Tech. Phys. USSR **2**, 125-127, 1935.

[6]) See C. M. van der Burgt, Ferroxcube material for piezomagnetic vibrators, Philips tech. Rev. **18**, 285-298, 1956/57.

frequency, see above), an inductance L of 0.395 henry is needed.

One of the advantages of this arrangement is that it is easy to produce with it a purely *sinusoidal* variation of the reciprocal capacitance. In that case an exact theoretical treatment is possible (we have the case of eq. (1) and (2), the Mathieu equation).

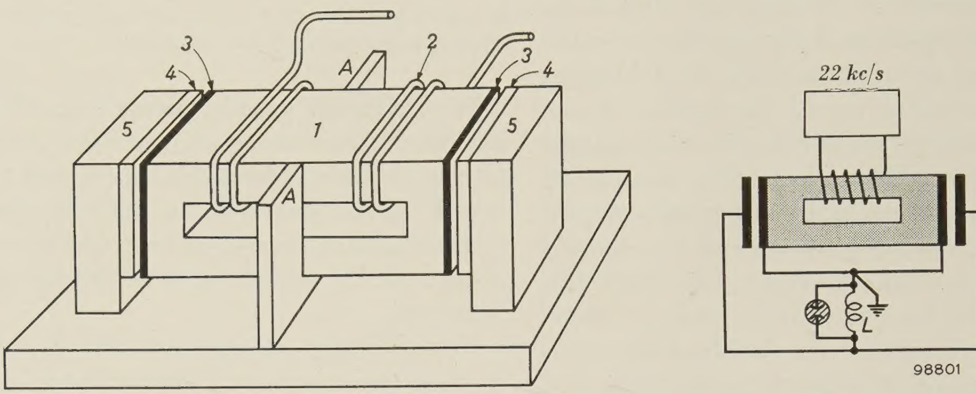


Fig. 5. Construction of a "magnetostrictive pump". *1* frame core of piezo-magnetic ferroxcube [6]), clamped at A; *2* core winding through which the current from an ultrasonic generator flows at a frequency of 22 kc/s; *3* metal plates attached to the core; *4* fixed plates spaced 80 μ from *3*; *5* insulating material. The basic diagram of the arrangement is shown on the right. The coil L must meet certain requirements regarding its inductance and its Q.

In particular it can be demonstrated that the parametric excitation of the natural frequency of the circuit calls for a certain minimum amplitude δ of the capacitor plates, and that this minimum amplitude is smaller the higher the Q of the resonant circuit ($Q = \omega L/R$, R being the series resistance of the coil). Provided δ/d_0 is sufficiently small, we find the condition (corresponding to the limit of the first stability region of the Mathieu equation [4])):

$$\frac{\delta}{d_0}\,Q > 2. \qquad (3)$$

With our ultrasonic oscillator the breaking strength of the core limits the amplitude δ to 1 micron. It follows from equation (3) that the coil in the resonant circuit must accordingly be constructed such that the Q of the circuit is at least 160.

The experiments confirm that this condition must indeed be fulfilled. *Fig. 6* shows two coils which both have the required inductance and more than a sufficient Q, one with an air core and the other with a ferroxcube core.

The amplitude reached by the voltage on the capacitor when the oscillation increases due to the pumping depends, in theory, solely upon the pump power. The power supplied to the circuit is $P = \frac{1}{2}\omega C_0 V^2/Q$. At $C_0 = 532$ pF and $Q = 200$, a voltage as high as $V = 3300$ V is reached at a power of only 1 W, which constitutes a scarcely noticeable load on the magnetostrictive resonator. A voltage as high as this would obviously cause our capacitor, with its air gap of 80 μ, to break down. Using the air-core coil in our arrangement it was indeed found necessary to limit the voltage in order to protect the capacitor. This was done by shunting a neon tube across the circuit, which is visible in the photograph of the complete set-up shown in *fig. 7*. This precaution is not required when the coil with

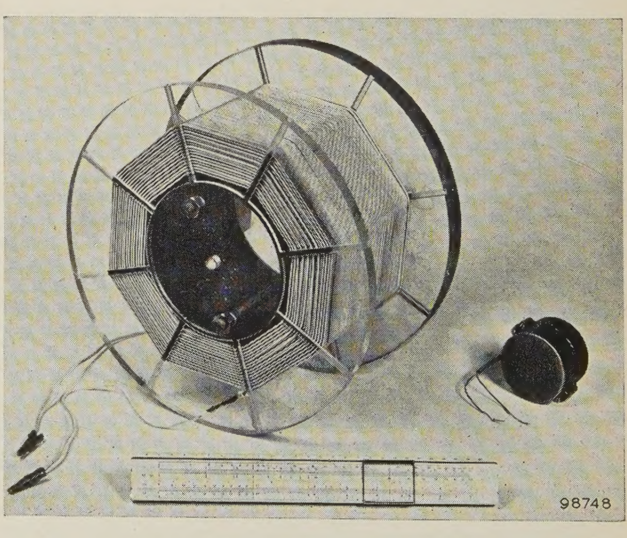


Fig. 6. Two coils used for demonstrating parametric amplification by means of the magnetostrictive pump. Left, coil with air core; right, coil with ferroxcube core.

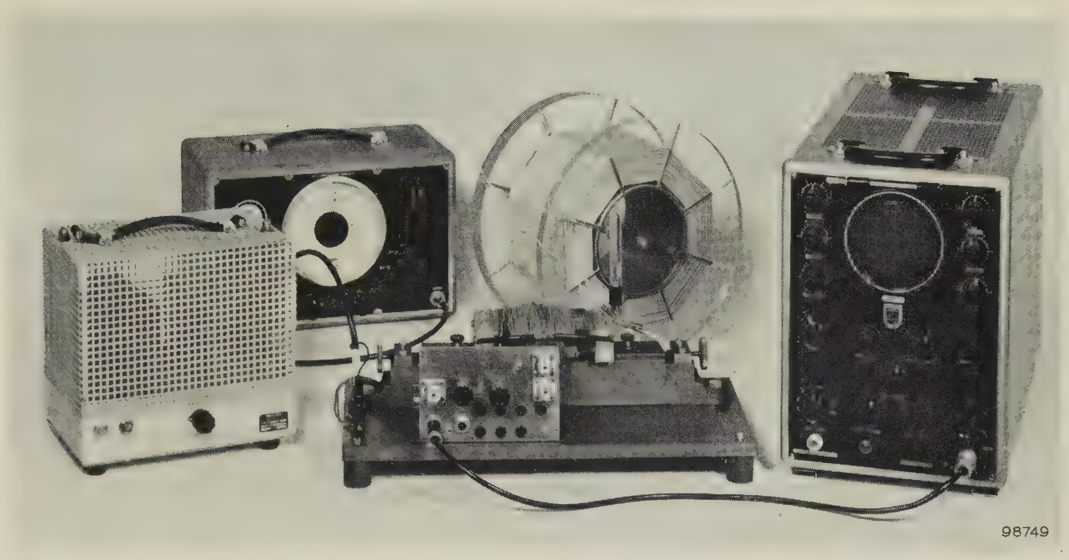


Fig. 7. The complete set-up. In the middle the magnetostrictive resonator with the air-core coil behind it (cf. fig. 6). A neon tube is shunted across the latter to limit the voltage. Left, the ultrasonic generator consisting of a signal generator and amplifier; right, oscilloscope for observing the amplified oscillation.

ferroxcube core is used: in this case the capacitor voltage does not rise above 250 V, owing to saturation of the ferroxcube.

The set-up illustrated can also be used as a simple means of demonstrating parametric amplification. The circuit is shown in *fig. 8*. The pump amplitude is set just below the threshold of spontaneous oscillation. As input signal we can take, for example, a signal of 11 kc/s, applied in the right phase from a signal generator. The signal can then be measured

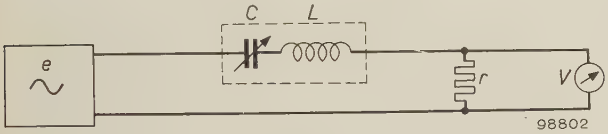


Fig. 8. Circuit for demonstrating parametric amplification with the set-up described; *e* signal source (signal generator), *r* load resistance, *V* voltmeter.

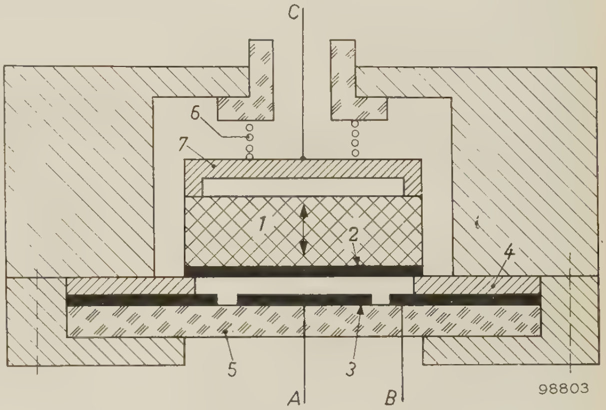


Fig. 9. Piezo-electric resonator as pump; pumping frequency 3 Mc/s. *1* resonating quartz crystal $19 \times 19 \times 0.95$ mm (X-cut), excited into the thickness compressional mode; *2* and *3* vapour-deposited silver layers; *4* metal spacing-ring 25 μ thick; *5* quartz-glass plate; *6* compression spring and *7* pressure plate; *A* and *B* connections for the inductance; *C* connection for exciting the quartz crystal.

at the output with the pump switched on and off. In this way we found a voltage amplification of 20 times.

We have made an arrangement similar to the one described above using a *piezo-electric* resonator as pump. The resonator consists of a quartz-crystal plate about 1 mm thick and with a surface area of about 20×20 mm^2, which is excited into the thickness compressional mode (*fig. 9*); the pump frequency is 3 Mc/s. The results obtained were similar to those obtained with the magnetostrictive pump.

B. BOLLÉE and G. de VRIES.

MODERN ACOUSTICAL ENGINEERING

II. ELECTRO-ACOUSTICAL INSTALLATIONS IN LARGE THEATRES

by D. KLEIS. 534.84:534.86:621.395.623.8

The various kinds of electro-acoustical equipment now available were surveyed in Part I of this article. The principles underlying their employment in order to improve the intelligibility of the spoken word, and in order to give music more "body" in halls with unsatisfactory acoustics, were also dealt with. Mention was likewise made of electro-acoustical installations for controlling the acoustics of a hall or auditorium. In recent years such installations have been built in several large theatres and opera houses, including the Palais de Chaillot in Paris and the Scala Theatre in Milan. These and other installations will be discussed here. It will be shown that many kinds of electro-acoustical equipment are necessary in such theatres, over and above installations for controlling their acoustics, and that closed-circuit television may also prove to be of value.

Introduction

The endeavour of modern acoustical engineering is to reproduce sound naturally. This means paying proper attention to the properties of the human ear and the acoustical properties of the hall or auditorium. Part I of this article [1]) dealt with the principles underlying the employment of electro-acoustical equipment, and certain conditions were deduced which have to be satisfied if natural sound reproduction is to be achieved.

One of the essential points that emerged is that direct and indirect sound have different functions: direct sound gives the hearer an impression of the sources and their spatial arrangement, while indirect sound gives him an impression of the hall. The characteristic feature of installations for controlling acoustics was stated to be the separate production of direct and indirect sound, each kind being given the volume and spatial distribution best suited to its purpose. Direct sound is reproduced, often stereophonically, by means of directional loudspeakers, and indirect sound is relayed through a delay and reverberation device to widely distributed, diffusely radiating speakers. It was further discussed in Part I how these methods might be employed (*a*) for obtaining the best possible reproduction of music and speech in halls and in the open air, (*b*) for supporting a live performance, by adapting the hall acoustics electro-acoustically to the type of performance being given, and (*c*) for introducing sound effects. At the same time mention was made of some general aspects of microphone positioning.

In Part II we shall start by studying the acoustical problems of theatres in general, go on to investigate what electro-acoustical facilities theatres require, and then discuss certain large installations [2]) which have been built in the following theatres and halls:

Teatro alla Scala in Milan,
Théâtre National Populaire (Palais de Chaillot) in Paris,
Grand Auditorium at the 1958 Brussels World Fair,
Gebouw voor Kunsten en Wetenschappen in The Hague.

Finally, a large public-address installation [3]), namely that at the Volkswagen factory at Wolfsburg, will be discussed.

Acoustical problems in theatres, and their solution

In Part I we saw that speech and various kinds of music make conflicting demands on the acoustics of a hall. That would not matter if a hall with suitable acoustics was available for each and every kind of performance. This is far from being the case even in many large towns; moreover, where suitable halls do exist, they often do not possess the technical facilities that a performance before a large audience requires. It is therefore inevitable that one and the

[1]) D. Kleis, Modern acoustical engineering, I. General principles, Philips tech. Rev. **20**, 309-326, 1958/59 (No. 11).

[2]) Designed and installed by the Projects Department of the Electro-Acoustics (E.L.A.) Division at Eindhoven, in consultation with the Acoustical Advisory Bureau and in collaboration with Philips organizations in the countries concerned and with technicians of the Commercial Department of E.L.A. Eindhoven.

[3]) Designed and installed by Deutsche Philips G.m.b.H.

same hall should have to serve for performances and gatherings of greatly differing kinds — symphony concerts, chamber music, opera, stage plays, meetings etc. Even if the question of acoustics be left aside, a concert hall is unsuitable for stage or opera performances because of lack of stage machinery, property rooms, stage lighting, dressing rooms and so on. However, reasons of this kind do not militate against the giving of concerts in a well-equipped theatre; it is only the acoustics of the stage and auditorium that make it undesirable to do so. In circumstances where one building has to suffice, then, it is logical to give it the full technical equipment of a theatre and to install electro-acoustical devices that make the auditorium equally suitable for musical performances.

It was demonstrated in the Grand Auditorium at the 1958 Brussels Exhibition that it is perfectly practicable and artistically permissible to put on performances of a widely differing character in a theatre that has been properly equipped from the electro-acoustical standpoint. During the six months of the Exhibition, the Auditorium, with its seating capacity of 2300 (*fig. 1*), was the scene of a great variety of meetings and shows, these taking place almost every evening and often during the afternoon as well; there were official addresses (including those at the ceremonial opening of the Exhibition), international congresses (with simultaneous interpreting), stage performances, operas, ballets, folk-dance programmes, song recitals, soloist and symphony concerts, choral performances, a film festival and a festival of electronic music. Thanks to an elaborate electro-acoustical installation it was possible for all this to take place to the satisfaction of both performers and the public.

It must not be concluded from the foregoing that the only reason for providing a theatre with an electro-acoustical installation is to make it suitable for concerts. More often the work is carried out in the first place with stage performances in mind. Provided it has been correctly designed and built, the installation serves the further purpose of making the theatre suitable for musical performances. In this way the building acquires a new usefulness.

Intelligibility

The biggest problem in many theatres is intelligibility. Imperfect intelligibility may be caused by an excessively long reverberation time, but it may also be due to the dimensions of the auditorium. Many modern theatres seat 1500 to 3000 people. In an auditorium of this size the sound may be so heavily attenuated, passing over the audience on its way to the back rows, that people seated there cannot hear it properly above the noise inevitably made by other members of the audience. The players have to make a disproportionate effort just to be understood, and this usually detracts from their performance without being entirely effective.

Fig. 1. The Grand Auditorium at the 1958 Brussels World Fair. The hall has a length of about 45 m, a cubic capacity of 15 000 m^3 and a seating capacity of 2300.

Irrespective of whether excessive reverberation or the size of the auditorium is the cause, poor intelligibility can be remedied by supplying additional direct sound from loudspeakers mounted on either side of the stage, and aiming these at the places where the stage proceedings are not being properly heard. As was made clear in Part I in the section headed *Direct sound*, sound from loudspeakers has the advantage, compared with the speaker's natural voice, of being beamed. What is more, if the loudspeakers are mounted high enough, the sound does not pass so closely over the heads of the people in the front of the auditorium and consequently suffers less absorption.

Where good intelligibility can be achieved with a loudspeaker signal not more than 10 dB louder than the direct sound from the actors on the stage, natural directional hearing can be maintained by introducing a slight delay into the signal (see Part I, p. 314). Sometimes the required delay can be obtained simply by mounting the loudspeakers in a particular position. However, if intelligibility necessitates raising the level of the loudspeaker signal more than 10 dB above that of the original direct sound, then stereophonic reproduction will be necessary if the audience are nevertheless to hear the stage proceedings from the right direction. The dangers of turning up the volume control too far

(and unhappily this is done all too often) were pointed out in Part I.

Though the direct sound may have to be amplified through 10 dB and sometimes even more, this does not mean that its loudness is increased in the same proportion. We shall demonstrate the truth of this in two cases, one for each cause of poor intelligibility.

In a large auditorium that nevertheless has a short reverberation time, high-pitched sounds are too weak on arrival at the rear, while low-pitched ones generally retain enough of their volume. Hence all the loudspeakers have to do is to reinforce the high-pitched sounds and so to restore the balance between these and the low-pitched ones. Now, high-pitched sounds contribute a great deal to intelligibility but very little to loudness; when therefore the loudspeakers are switched on or off, the difference in intelligibility is striking, though the difference in loudness is scarcely perceptible.

In an auditorium having too long a reverberation time the intensities of the direct and indirect sound are badly out of proportion for speech — say 1 : 20. If the intensity ratio is raised to 20 : 20 by means of an electro-acoustical installation, then the direct sound will be undergoing twenty-fold amplification, i.e. being amplified through 13 dB; but the total volume will only increase in the proportion of 21 : 40, i.e. by 3 dB. (Since it is mainly the high-pitched sounds that undergo amplification, the increase in overall loudness is still less.)

The foregoing will have made it clear that the term "amplifying equipment" is scarcely justified when applied to the type of installation described here, for there is hardly any question of an increase in loudness. On the other hand it is perfectly proper to use the term in connection with equipment for relaying sound in the open air, where the original sounds, both high-pitched and low-pitched, are too weak some distance away from the speaker.

There may be places in an auditorium — under a low balcony, for example — where the original sound does not penetrate sufficiently and where, often enough, the sound coming from the loudspeaker columns at the front of the auditorium is also too weak. Intelligibility in such places can be improved by fitting loudspeakers on the spot. The sound they give must be suitably delayed, to prevent the hearers getting the impression that it is coming from somewhere in their vicinity. (Here again there is usually no question of true amplification.)

Music

Music is an essential element in operas, operettas, revues, shows and also in many stage plays. Having dealt with intelligibility as the primary acoustical problem in theatres, we would reserve second place for the problem of making music sound as it should. Often, where intelligibility is good, music will not sound entirely satisfactory, the reason being that music requires a longer reverberation time than is compatible with good intelligibility. Added to this is the fact that the interior architecture of a theatre must satisfy certain visual requirements and these sometimes conflict with acoustical ones.

The orchestra providing the music for an opera or a play must not impede the audience's view of the stage. Accordingly, it is relegated to the orchestra pit in front of the stage (*fig. 2*), and there most of its members generally have the proscenium above their heads. This location, especially the part of the pit that is covered over, is acoustically a very bad one. The rather feeble impression frequently made by the overture to an opera, even when the orchestra numbers sixty or more musicians, may be attributed to their unfavourable location. For that very reason the orchestra platform of the Radio City Theater in New York is hydraulically raised whenever the orchestra is giving a performance which is not an accompaniment to some stage spectacle.

A further visual requirement is that the view of the stage should be good from every seat in the theatre. It may be satisfied by the classical theatre interior, in which several balconies and tiers of boxes rise one above the other. The arrangement is not a bad one from the viewpoint of intelligibility either (provided at least that the auditorium is not so lofty that the upper balconies are excessively remote from the stage). Even so, the balconies and boxes absorb a great deal of sound, hindering the diffusion of music and making the reverberation time too short. Needless to say, this applies as much to voices from the stage as to the music provided by the orchestra.

The lack of diffuseness and reverberation can be remedied by picking up the music with directional microphones, delaying it, and reproducing it with delay and diffuse reverberation via loudspeakers distributed around the auditorium (see under *Indirect sound* in Part I). This is what has been referred to in the past as stereo-reverberation [4]). In the meantime the new term *ambiophony* has been introduced for this electro-acoustical technique [5]).

The music played in the orchestra pit can be made to sound better if it is backed up by directional loudspeakers placed on either side of the proscenium

---

[4]) R. Vermeulen, Stereo-reverberation, Philips tech. Rev. 17, 258-266, 1955/56. See also [1]).

[5]) See footnote [11]) in Part I of this article.

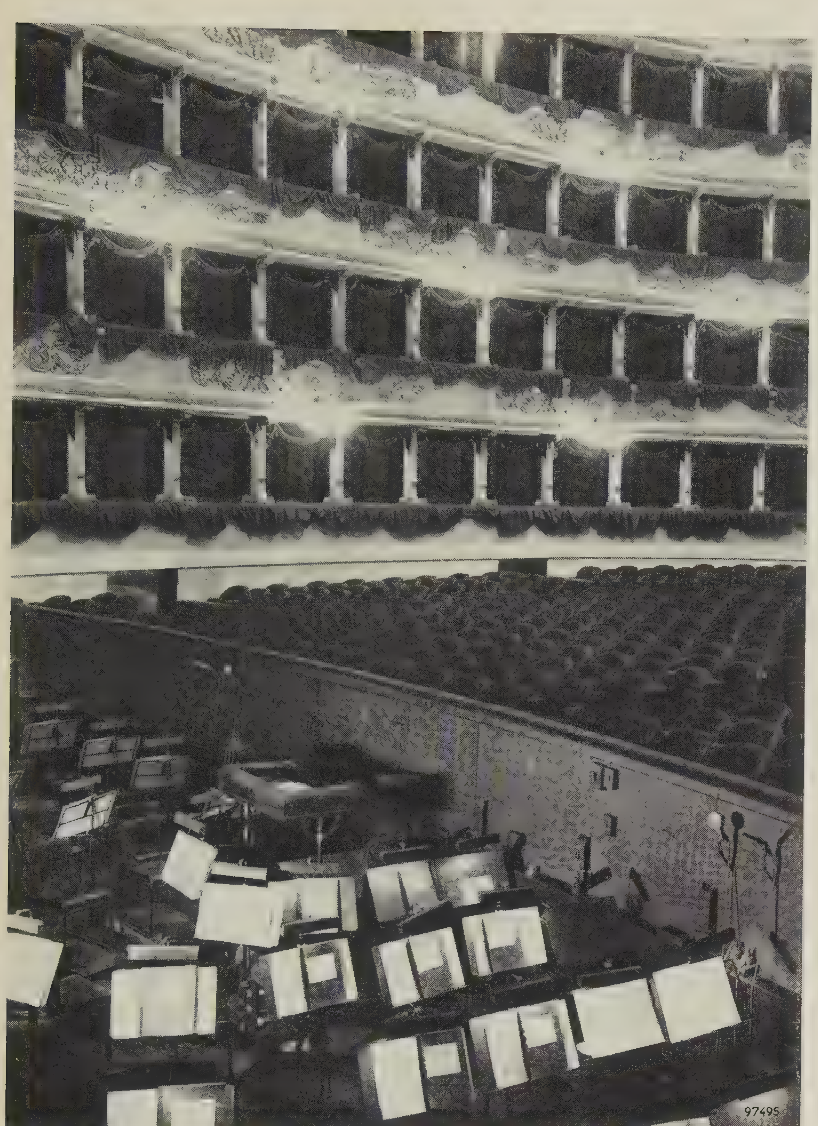


Fig. 2. The auditorium of the Scala theatre, Milan. The acoustics for music are favoured neither by the conventional siting of the orchestra in an orchestra pit, nor by the boxes (only four of the six tiers can be seen in the photograph).

arch — the same loudspeakers in fact that are used for improving intelligibility. By dint of such backing, the orchestra is placed "on stage" acoustically and so lifted out of the unfavourable location to which it is tied for visual reasons.

Reproduction by these loudspeakers ought to be stereophonic in order to make the music "transparent" (i.e. in order to make is possible to distinguish individual instruments). Owing to the limitations on space in the orchestra pit, which is often overcrowded, it is usually impossible to position the microphones in an ideal stereophonic layout. Generally, however, good results can be obtained by mounting the microphones along the partition between the orchestra and the audience, and dividing them electrically into two groups, the left-hand group being linked via an amplifier to loudspeakers on the left of the stage, the right-hand group via another amplifier to those on the right of the stage. Microphones that have been mounted for this purpose may be seen in fig. 2. Usually the ambiophonic installation will be employed to give additional backing to music originating in the orchestra pit.

Some theatres possess an organ which is sometimes built into a side wall of the stage. A location like this is particularly bad from the acoustical standpoint: most of the sound vanishes into the stage superstructure, which is highly absorbent, and the rest can only reach the auditorium by passing through the wings. It is advisable in fact to "put the organ on stage" in the acoustical sense by employing loudspeakers in support, as is done for the orchestra. Further support, by means of loudspeakers placed around the auditorium and giving ambiophonic (diffuse, delayed and reverberant) sound, makes it possible to render the acoustics of the auditorium almost ideal for organ music [6]).

The acoustics as they affect the performer

What has been said so far concerns auditorium acoustics as perceived by the audience. Acoustics as they affect musicians on the stage or in the orchestra pit are certainly of no less importance. In a good concert-hall each member of the orchestra is enabled by reflections from the wall and ceiling of the podium to hear the playing of the other musicians. In an opera house, on the other hand, it is rare for the stage setting to have acoustically hard walls and a closed ceiling (this would make scene-shifting an extremely heavy job). Opera scenery usually consists of cloth stretched over a framework of laths, and the setting is open at the top, so that acoustically the stage resembles a place in the open air. In consequence, the singers on stage do not hear

[6]) This has been possible in the Philips Theatre at Eindhoven since as long ago as 1954; see fig. 7 in the article cited in [4]).

one another at all well and have no idea of how their combined efforts sound in the auditorium. The musician in the orchestra pit hears little more than the instruments in his immediate vicinity, and he too has no idea of the impression made in the auditorium.

These drawbacks for the performer are considerably alleviated by the electro-acoustical equipment described above; direct sound from the loudspeaker columns beside the stage and indirect sound from the speakers around the auditorium travel directly or are reflected into the orchestra pit and the stage as well as into the auditorium, and in this way the performers get an impression of what is being heard by the audience. The extent to which they do so depends very much on local circumstances. There is in principle a limit to this desirable effect in that the microphones pick up some of the returning sound, with acoustic feedback as a result. Naturally, this must not be allowed to result in accentuation of one or more frequencies. However, one way of obviating the above difficulties for the performer is conceivable, that being to have special loudspeakers for the performers, placed in such a way that the microphones only pick up a very small fraction of the sound from them. It is the orchestra's difficulties that are easiest to remedy in this way, for its members remain in place; small loudspeakers fixed to chairbacks or music-stands, close to the musician's head, serve the purpose quite satisfactorily.

To find a solution for the artistes on the stage who must have plenty of freedom of movement, is not so easy. Here use can be made of loudspeaker columns facing the stage and so positioned that as little as possible of their sound reaches the microphones.

Operation

No extra staff are required for operating the electro-acoustical installations so far mentioned. The microphones and loudspeakers have permanent positions (generally such that they are invisible to the audience, or in any case such that they are inconspicuous). The microphone and loudspeaker cables are likewise permanent (*fig. 3*) and all lead to a control room, which accommodates the pre-amplifiers, power amplifiers and delay device. We shall come back to the control room later on. If reserve cables are laid at the same time as the main installation is being built, it will be easy later on to make extra microphone points in places where these may be desired.

Despite differences in auditorium acoustics and resulting differences between installations, it always proves possible in practice to build up the latter out of standard units, provided these are combined in the right manner. The installation is once and for all adapted to the *auditorium* by the positioning of the loudspeakers, the delays that the ambiophonic equipment has been adjusted to give, and so on. Adaptation to *performances* of various kinds can be obtained by exercising a suitable choice of the intensity ratios and reverberation times; the choice is made by operating a selector switch having positions for "play", "opera", "chamber music", "symphonic music", "soloist concert", "organ", etc. Operating routines can in this way be limited to switching on, carrying out a set inspection programme, and switching the selector to the right position. Such work can be done by a member of the normal technical staff, such as the lighting assistant.

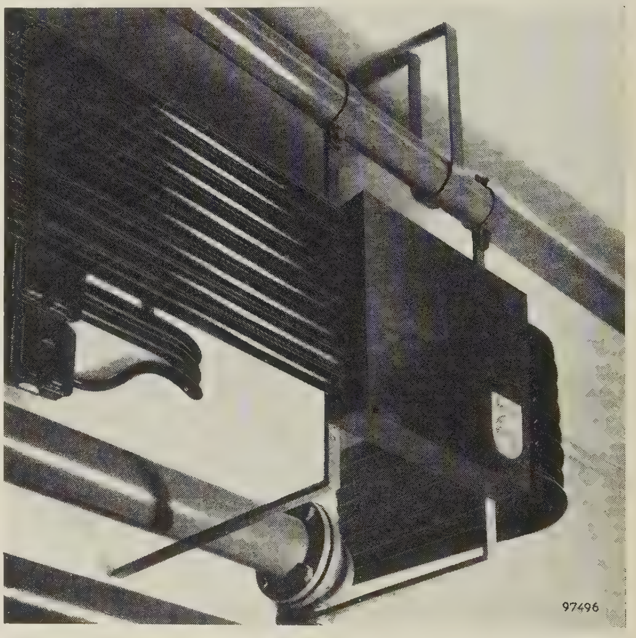


Fig. 3. All the cables of the electro-acoustical installation in the Scala are enclosed in steel conduits.

Electro-acoustical service facilities in theatres

Apart from the above electro-acoustical installations, which have an artistic function, there is a need in theatres for electro-acoustical equipment providing audience, artistes and staff with certain facilities that improve or simplify the everyday routine of the house. Like the others, these "service" installations do not normally require special staff to operate them.

We shall now go on to review a series of installations of this kind.

Monitoring system

If the everyday routine of the theatre is to go smoothly, certain persons outside the auditorium must be able to follow the performance in order to know when to come into action. This applies amongst others to the artistes in their dressing rooms, musicians who have to play behind the scenes during a performance, ballet groups, extras, scene-shifters, ushers, porters, and stage-lighting, kitchen and wardrobe-personnel.

Theatres like the Scala and the Palais de Chaillot have a monitoring system for this purpose. It consists of an amplifier whose input signal is supplied by microphones in the auditorium and which feeds loudspeakers in dressing rooms and other service rooms. The loudspeakers in some of these rooms are fitted with a volume control or on-off switch.

Paging system for performers

One of the responsibilities of the stage manager is to warn actors, extras and musicians a short time before they have to appear or perform. For this purpose use is generally made of the loudspeakers and cables of the monitoring system. Just to one side of the stage, the stage manager has a control desk with microphone and amplifier (*fig. 4*) at his disposal. By means of keys or push-buttons he is able to connect up one or more loudspeakers of the monitoring system to his own amplifier, so that he can address certain individual performers or groups of performers. The employment of a special circuit in which the loudspeaker lines are three-core cables makes it possible for the caller to put the volume controls and on-off switches out of action while he is talking; thus the call is always heard at full volume. The principle of dynamic compression is applied in the amplifier for the paging system; the advantage is that calls made over the system are always equally loud, the volume being independent within wide limits of the distance between caller and microphone, and that reproduction is free from distortion because the compressor makes overloading of the amplifier impossible.

Hearing-aid installation

In a theatre or concert hall, a hearing-aid is not a very satisfactory device for the hard of hearing because it gives no impression of direction. In consequence, the wearer is unable to separate disturbing sound (reverberation and audience noise) from music or the voices of the actors. Hence such noise is far more tiresome for him than for a person with normal hearing. Things are likely to be much improved for the hard of hearing, then, if they can be offered a sound signal that is practically free from interference. This can be achieved by picking up the sounds from stage or platform with directional microphones, so positioned that they are little affected by noise and reverberation from the auditorium, and feeding the signal thus obtained to a loop of wire laid round the auditorium. The audiofrequency current in the loop creates a magnetic field that induces a voltage in the pick-up coils [7]) of normal hearing aids. The voltage induced is to all intents and purposes free from interference, and has the same value throughout the auditorium. With this installation, therefore, there is no need for the hard of hearing to occupy seats in the front of the auditorium, or seats reserved for them and provided with connections for special earpieces. Some theatres having a loop installation hire hearing-aids with a pick-up coil to those of the public who want them and do not possess their own.

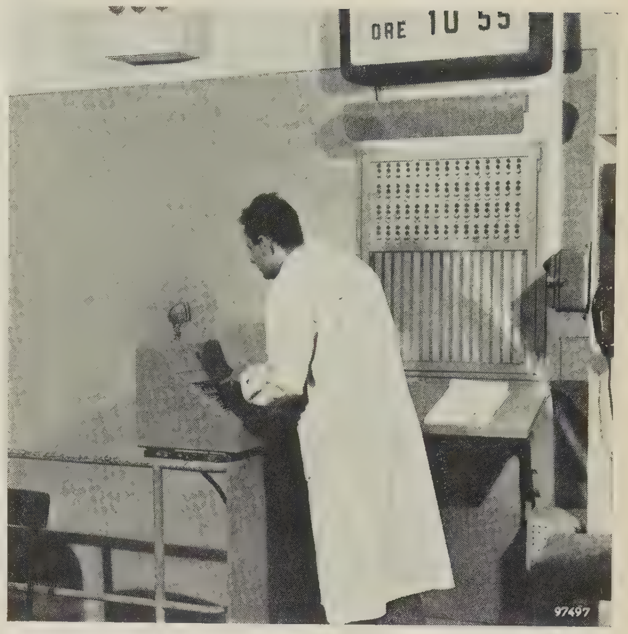


Fig. 4. The stage manager at the Scala has a control desk with a microphone, amplifier and switches; the desk allows him to contact artistes, individually or in groups, via the cables and loudspeakers of the monitoring system, to call them "on stage".

Monitor system for latecomers

It is a well-known fact that, at any performance, some members of the audience arrive late. In large theatres, in order to spare the punctual from the annoyance caused by latecomers, the auditorium doors are closed about one minute before the start of the performance and only re-opened during the short interval that follows the first act or first item on the musical programme. In this way the late-

[7]) Philips tech. Rev. **15**, 41-42, 1953/54.

comers miss a considerable part of the programme. For the benefit of latecomers at the Scala and the Chaillot theatre, the foyers have been equipped with loudspeakers connected to the monitory system described above. During the main interval the loudspeakers can be used for playing back music from gramophone records or magnetic tape. If a foyer is provided in addition with a microphone point and a pre-amplifier, the foyer itself becomes suitable for independent use as a hall where lectures, music recitals and the like can be given.

Television links

Although it is not classifiable as electro-acoustical equipment, closed-circuit television must be given mention here because there does exist a technical connection between the two, and television links can be extraordinarily useful in theatres.

In the first place, television is useful where it is thought desirable to display events on the stage in certain places outside the auditorium. An example is the television installation in the Palais de Chaillot, where latecomers can see the first act of the play from one of the foyers. For this purpose the cinema projection cabin has been equipped with a television camera fitted with a telephoto lens. The cabin also houses a small television transmitter. However, instead of feeding an aerial, the transmitter passes a carrier wave modulated with the video signal into a cable which conveys it to a number of ordinary television receivers in one of the foyers. The installation can, if necessary, be extended to feed extra receivers in other places such as managers' offices, the lighting cabin and so on.

Television has found a different application at the Scala, where it serves to make the conductor visible to members of the orchestra or choir who have no direct view of him. We shall return to this application when discussing that particular theatre.

Paging system for the public

A paging system can be a great help towards keeping a performance running to schedule, particularly in large theatres where during the interval the audience disperses into corridors, stairways and foyers. The system can be used to warn the public that the show is about to begin or that the interval is coming to an end, and to direct latecomers to a particular foyer. If the lines to these loudspeakers pass through the stage manager's control desk, he is able to announce the approach of an interval to latecomers, so that they can make their way to the auditorium. In case of emergency members of the audience can be called by name.

The Palais de Chaillot possesses a particularly convenient system of this kind. Reminders and instructions to the public, interspersed with suitable music, are recorded on tape prior to the performance. The playing back of the tape is initiated a certain time before the start of the show and before the end of the interval, and in this way members of the public are efficiently and affably paged into the auditorium, or into the foyer with the television sets if they have arrived late.

Simultaneous interpreting installations

In virtue of their wide range of facilities, large theatres are highly suitable for congresses. If the congress is an international one it may be essential that translations of speeches and discussions should be supplied in some form or another. Providing oral translations after each speech costs a great deal of time, even if they are nothing but résumés, which in any case have the disadvantage of incompleteness. For this reason the method most commonly used nowadays is to give simultaneous translations in various languages via an installation designed for the purpose.

A row of interpreters' cabins is erected behind a double glass panel looking on to the congress hall (*fig.* 5). By switching a selector, each interpreter

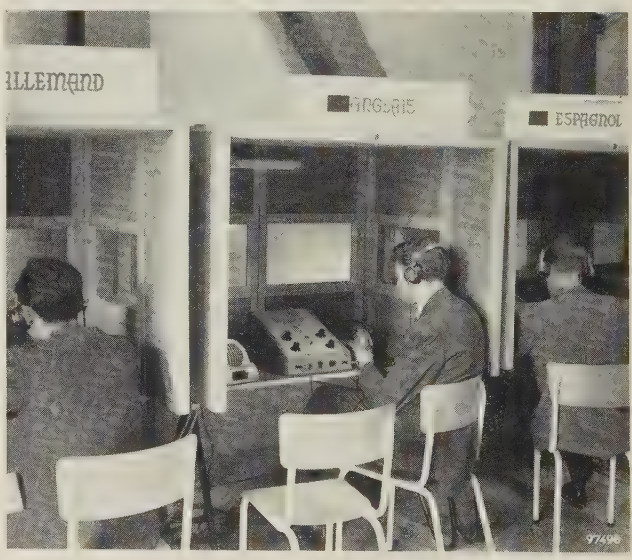


Fig. 5. Interpreters' cabins of the simultaneous interpreting installation in the Grand Auditorium at the 1958 Brussels Exhibition.

can hear in his headphones either the speaker in the hall or one of the other interpreters; he gives his own translation into a microphone. (Sometimes interpreters translate from a language which suits them better than the language of the speaker.)

Two kinds of interpreting installation exist. Under the older system each seat in the hall is provided with a socket for headphones and with a selector for different languages [8]). The need to lay a large amount of cable makes an installation of this kind rather expensive. The "wireless" system is much cheaper; under this system each interpreter's rendering is modulated on a "carrier wave", the set of modulated carriers being passed through one loop laid around the auditorium like the loop in a hearing-aid installation. Each person attending the congress is given a special hearing-aid (in reality a small radio receiver — see *fig. 6*) equipped with a pick-up coil and a selector for the various languages. Thus equipped, participants are able to listen to the original speech (which may be backed up by an electro-acoustical installation) or to the translation thereof which suits them best. The carrier waves can be picked up outside the hall, and the wireless system therefore lacks the advantage of secrecy; under the system first referred to, secrecy is complete. Philips have equipped several buildings with these wireless interpreting installations, some with four channels (the carrier frequencies being 74, 86, 98 and 110 kc/s) and some with six (carrier frequencies of 50 and 62 kc/s plus the four just mentioned). Amplitude modulation is employed. The power output to the loop is generally no more than 2 or 3 W per channel.

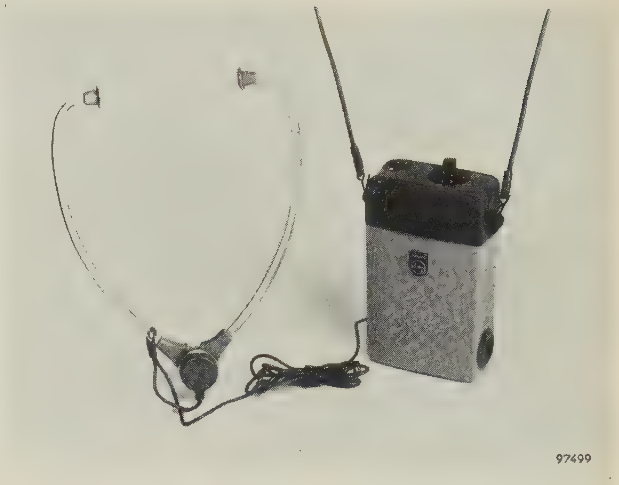


Fig. 6. Personal transistor receiver used in conjunction with a simultaneous-interpreting installation. At the top left is the volume control and top right the channel selector. The installations have either six or four channels.

Equipment in the acoustic control room

Theatre installations serving mainly or incidentally for sound effects call for a special operator who is able to supervise and check the whole electro-acoustical installation from one central point, that being the acoustic control room. The position and layout of the control room should be such as to allow the operator seated behind his control desk to see the stage through a sound-insulating window.

All microphone and loudspeaker lines terminate in the control room (*fig.* 7), where connections to the internal and public telephone systems are available; often there are connections to land lines going to broadcasting and television centres. Besides the central control desk, other desks for special purposes such as radio broadcasts may be present. The control room is equipped with gramophones and magnetic

Fig. 7. An example of a sound control room for a large electro-acoustical installation. The photograph shows part of the control room of the Grand Auditorium at the 1958 Brussels Exhibition. The central control desk is in the foreground, the broadcasting desk to the rear. Monitoring loudspeakers may be seen in the top left-hand corner.

[8]) See for example N. A. J. Voorhoeve and J. P. Bourdrez, The electro-acoustic installation in the League of Nations Palace in Geneva, Philips tech. Rev. **3**, 322-330, 1938.

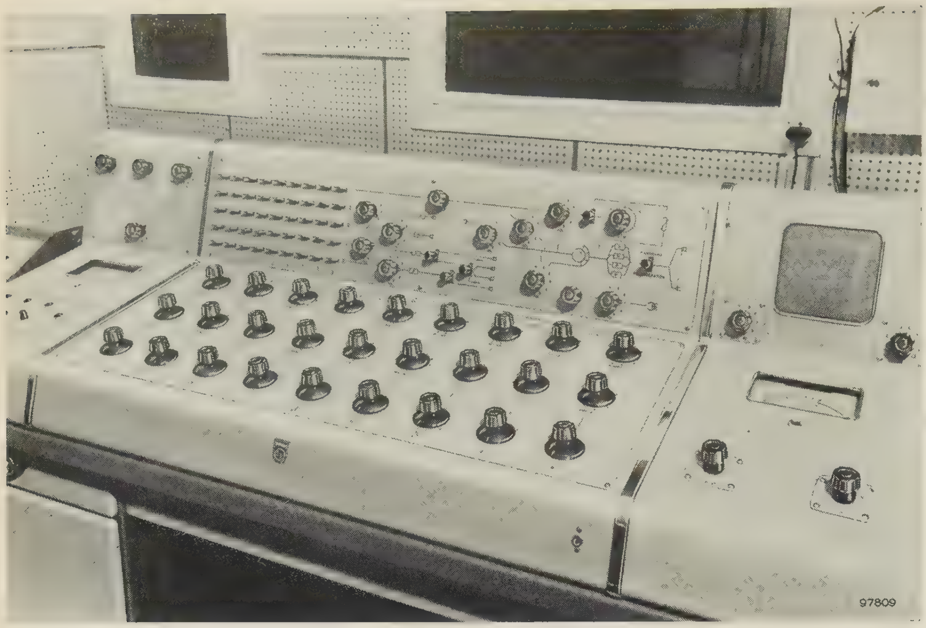


Fig. 8. The central control desk in the Palais de Chaillot. The nearest of the three rows of nine knobs consists of volume controls, the middle and back rows being low-note and high-note tone controls. The sets of three controls, taken from left to right, regulate six microphone channels, one gramophone channel and two tape-recorder channels. On the back panel, at the extreme right of the central section, is the panorama-reverberation switch, discussed later in the article (p. 66).

recording and playback apparatus and it accommodates all the amplifiers, standby amplifiers and monitoring equipment.

Experience has shown that a total of 25 microphone points on and near the stage and in the auditorium is adequate for all eventualities. Some points are in constant use and others are only used temporarily, when certain scenes require them. If the scenes change rapidly, microphones can be plugged in prior to the scene in which they are required; all that is necessary during the change is to place them in position.

It has further been found that the number of microphones in use at any one time rarely exceeds six. However, more than six were necessary on occasion in the Grand Auditorium at the Brussels World Fair (see the description of this installation, below). A switchboard is mounted within reach of the operator, allowing him to switch up to six microphones (or groups of microphones in parallel) through to the control desk. Low-impedance (50 ohm) microphones are employed in theatres, to obviate high-note losses due to the long cables; the microphone inputs in the desk are matched to this impedance.

The gramophones are of the type used in broadcasting studios. They are duplicated in order to allow gramophone records to be played without a break. They have their own amplifiers, which incorporate a correction network designed for the usual record-cutting characteristics [9]). One or other of the gramophones can be connected to an input of the central control desk by means of a selector switch.

The tape-recorders are also of the professional type. Two or three tape speeds are possible and there are generally two channels, in order to allow for stereophonic reproduction. Usually a pair of tape-recorders, together with their amplifiers, are built into a recording desk provided with the necessary record and playback switching arrangements.

The central control desk forms a link between a group of signal sources and a group of amplifier and other inputs. The former group comprises:

- the microphones (generally six channels),
- the gramophone in operation (usually one channel), and
- the tape-recorder used for playing-back (two channels, for stereophony).

The latter group comprises:

- the inputs of the power amplifiers driving the various loudspeaker groups,
- the input of the ambiophony installation,
- the input of the recording desk, and possibly
- the input of the broadcasting desk.

On the central control desk (*fig. 8*) may be found all the switches and controls that have to be manipulated during a performance or when a recording is being made. The desk also contains all the pre-amplifiers.

Each input channel of the desk has its own pre-amplifier and volume control and its own tone controls for low and high notes. By switching a selector it is possible to tap any of the channels at a point in front of these controls, and so to listen in to the signal and read its level on a dB meter. The output channels likewise have separate volume controls. Connections between input and output channels are made by means of a cross-bar switchboard, the principle of which is shown in *fig. 9*.

[9]) See for example Philips tech. Rev. **17**, 104, 1955/56 or **18**, 239, 1956/57.

The power amplifiers are accommodated in standardized steel cabinets. Each cabinet holds four amplifiers and one in reserve, and each has a monitoring panel. On the panel are a loudspeaker, an output meter, and a selector switch; with these it is possible to listen in to and measure the output from each amplifier. By pressing a button, the standby amplifier can be put into operation in place of one that developed a fault; the standby is always ready for immediate operation because the heaters of its tubes are kept warm. The changeover is not noticeable in the auditorium.

The ambiophony equipment is also housed in a standard steel cabinet (fig. 23 in Part I). Besides being fed to the loudspeakers around the auditorium, the output from the equipment goes to the controls of the recording and broadcasting desks, so that electrically generated reverberation can be blended into recordings and radio broadcasts.

A small part of the central control desk is generally reserved for the controlling, mixing, measurement and auditory monitoring of the signals originating in the auditorium microphones belonging to the general monitoring system. The output signal from this part of the desk is fed to the amplifiers of the general monitoring system, to the public loudspeakers in the foyer and to the induction loop of the hearing aid installation.

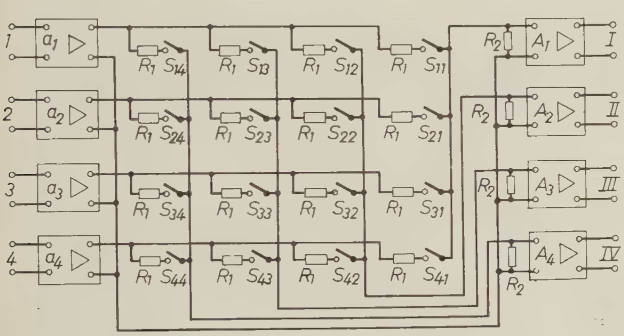


Fig. 9. Block-diagram of a cross-bar switchboard allowing interconnection of multiple inputs with multiple outputs on a central control desk. In the diagram there are four inputs (*1 . . . 4*) and four outputs (*I . . . IV*). $a_1 \dots a_4$: pre-amplifiers. $A_1 \dots A_4$: line amplifiers. R_1 and R_2 are resistors with high and low values respectively. Suppose (e.g.) that switches S_{23} and S_{43} below are closed: in this case pre-amplifiers a_2 and a_4 will deliver signals to line amplifier A_3 via voltage dividers R_1-R_2. The signals are therefore mixed and amplified on arrival in output channel *III*. The high resistances denoted by R_1 prevent cross-talk between the pre-amplifiers.

Although we have mentioned various theatres by name, we have tried to keep the foregoing account as general as possible. We shall now go on to describe more fully certain large installations already in existence. These descriptions will show that electroacoustical installations, while having the same basic pattern, exhibit individual differences due to local circumstances or personal preferences.

Teatro alla Scala, Milan

The *Teatro alla Scala* was built by Piermarini in 1778 on the former site of a church founded by Beatrice della Scala. The building consists of a large auditorium for operas and concerts, and the "Piccolo Scala", a much smaller auditorium in which chamber music and less elaborate operas are performed and which will not be discussed further here. The large auditorium (fig. 2) has the shape of a horseshoe; it seats about 2500 and there are six tiers of boxes one above the other. The theatre owes its renown as the finest opera house in the world to both the perfection of the performances given there and the magnificence of its stage settings.

In 1954 a committee set up by the management came to the conclusion that a suitable acoustical installation would help to give audiences an even stronger impression of being involved in events on the stage. They further considered that such an installation would also be the answer to the variety of technical problems then existing. The most important of these problems were:

(1) Musical groups and choirs placed at the side of or behind the stage, for the purpose of creating certain sound effects during operatic performances, could not be heard properly in the auditorium because of the damping caused by the scenery.
(2) These musicians and singers were in the way of actors, dance groups and crowds going on and leaving the stage (it is not unusual for more than 200 persons to enter and exit within a short interval!).
(3) Members of the orchestra and choir behind the scenes were unable to see the conductor. The difficulty was overcome by placing them under the baton of a second conductor who had to watch the principal conductor through an opening in the scenery (*fig. 10*).
(4) Actors awaiting their cues behind the scenes were unable to hear the orchestra and follow the stage action properly; consequently it was difficult for them to pick the right instant to go on stage.

It was possible to settle the first three problems once and for all by fitting up a separate studio for musicians and singers not performing on the stage or in the orchestra pit. A closed circuit television link enables these performers to see the conductor. Whenever they are not playing or singing themselves, they can follow the performance via loudspeakers forming part of the monitoring system.

They play or sing when instructed by the conductor to do so and their performance is reproduced through loudspeakers in the auditorium. The lack of space, and the hindrance musicians represented for the actors and extras, and *vice versa*, have been effectively remedied in this way. Moreover, for the purpose of musical performances the studio is acoustically much superior to the confined space behind the stage, where the sound was absorbed by scenery. As the microphones and the loudspeakers are in different rooms, there is no danger of acoustic feedback; nor, therefore, is there any limitation on the positioning of microphones in the studio and on the sound effects that can be produced there.

Fig. 10. At one time it was necessary in the Scala to place members of the orchestra behind the stage to provide music "off". Being unable to see the conductor of the orchestra, these musicians had to play under the direction of an "intermediary" who watched the conductor through a hole in the scenery and copied his movements. They now play in a studio where they can see the conductor on a television screen; their performance is reproduced by loudspeakers in the auditorium.

Problem number (4), the inability of actors to hear properly while awaiting their cues, has been settled by installing a special monitoring system: microphones trained on the orchestra and the stage have been mounted on the inside of the partition between orchestra and auditorium (fig. 2), and loudspeakers have been set up off stage.

In regard now to the acoustics of the auditorium, it may be noted that the numerous boxes do a great deal to absorb sound. As a result, the reverberation time is fairly short (1.55 s for 500 c/s) when the auditorium is empty and even shorter when it is full. The short reverberation time favours intelligibility, and in this respect the acoustics of the auditorium require no correction. On the other hand there was every reason to employ ambiophony, since it would be desirable not only during symphony concerts but also at times during operatic performances, when a certain scene required it.

In close consultation with the technical staff of the Scala Philips designed an acoustical installation that caters for all the needs of the theatre. Its "première" took place on the 7th December 1955, when Mozart's "Magic Flute" was performed under Herbert von Karajan. All the music formerly played off stage was now relayed from the studio, the musicians there following the conductor via the television link. At the same time large-scale use was made of the facilities for spatial reproduction — stereophony, ambiophony and distant-source effects — that the installation offers.

The installation can be divided into two parts, one for supporting the actual performance and one covering the monitoring system, paging system and other facilities.

Equipment for supporting the performance

Microphones. A total of 25 microphone points have been provided on the stage and in the studio. Sensitive electrodynamic microphones of type EL 6040 are plugged into these points as required.

Acoustic control room. The complete block diagram of the acoustical installation in the Scala appears in *fig. 11*. *Fig. 12* shows what combinations are possible between the various groups of microphones and loudspeakers. Most of the equipment shown in these diagrams is accommodated in the control room, located between the small and large auditoriums and with view of both stages.

The 25 microphone points on the large stage lead to a switchboard D (fig. 11). Following the instructions in the sound scenario, the operator uses this panel to connect up the microphones M_1 about to be used, with the microphone inputs (which are five in number) of the central control desk. The latter also has a tape-recorder input T and a gramophone input G. The main uses to which the tape-recorder is put are to play back sound effects and to record ballet music that is required for later reproduction at rehearsals or for instructional purposes in the ballet school. The tape-recorder forming part of this installation has only subordinate importance and is not therefore designed for stereophony.

Each of the seven channels M_1, T and G has two pre-amplifiers between which there is a volume control P_1. These controls are not operated from the control room, but are mounted on a correction desk under the control of the sound *régisseur* (see below).

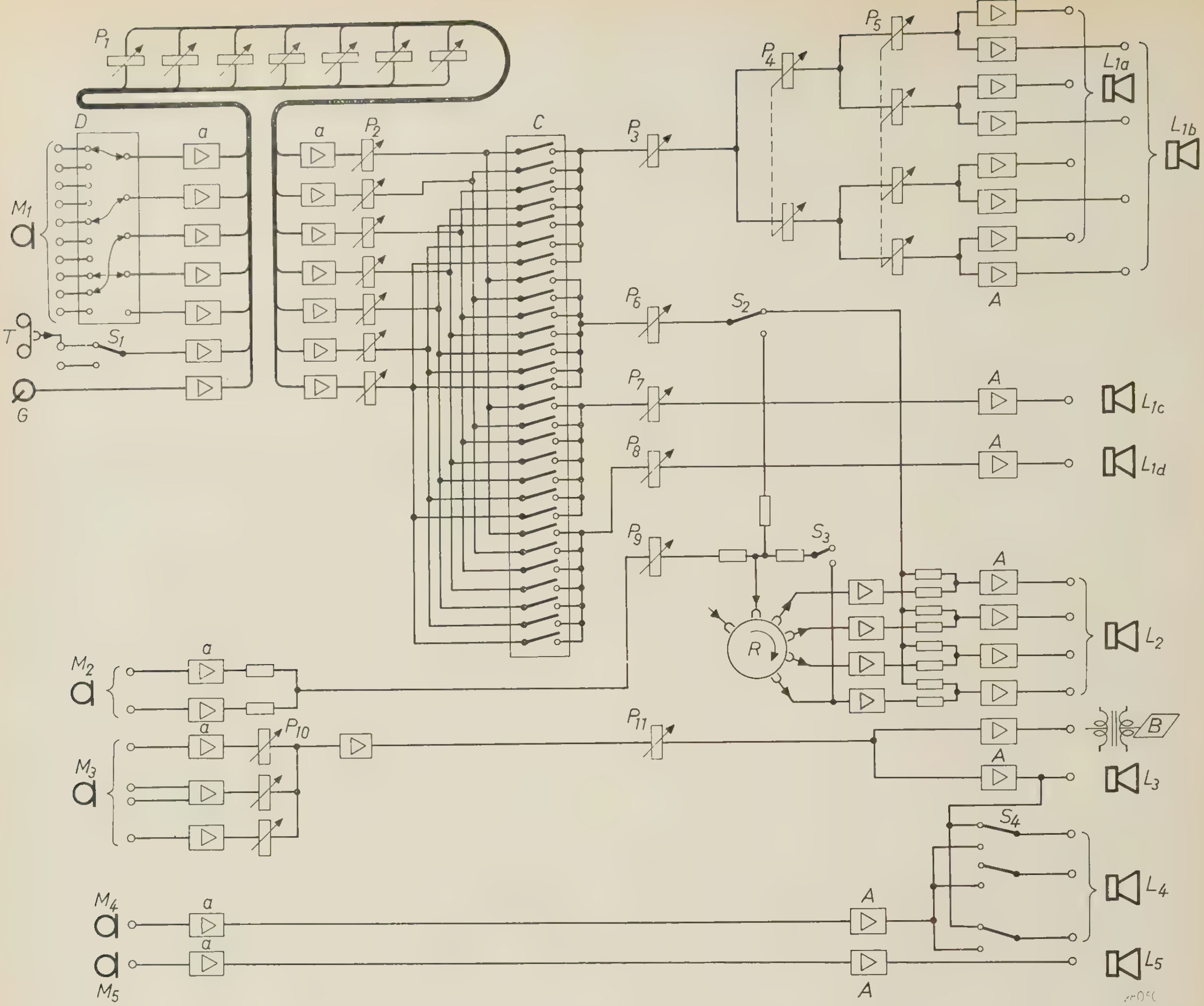


Fig. 11. Block circuit covering the entire electro-acoustical installation (except the intercommunications system) in the Scala.
a: pre-amplifiers. *A*: power amplifiers (120 W). *B*: induction loop for the hard of hearing. *C*: cross-bar switchboard. *D*: microphone switchboard. *G*: gramophone pick-up. L_{1a} and L_{1b}: low-note and high-note loudspeakers mounted around the proscenium arch. L_{1c}: loudspeakers mounted above the stage. L_{1d}: loudspeakers mounted on the stage. L_2, loudspeakers round the ceiling. L_3: loudspeakers in corridors: foyers etc. L_4: loudspeakers in dressing rooms etc. L_5: loudspeakers in the wings. M_1: microphone points on stage and in the studio (only 10 are shown out of a total of 25). M_2: microphones above the stage, for reverberant sound. M_3: monitoring microphones. M_4: stage manager's microphone (fig. 4). M_5: microphones in the orchestra pit (fig. 2). P_1: volume controls on the sound *régisseur's* correction desk. P_2: volume controls in the input channels of the central control desk. P_3: volume controls for loudspeakers L_{1a} and L_{1b}. P_4,P_5: panoramic potentiometers (L_{1a},L_{1b}). P_6: volume control for mixing reverberation into recordings or into the signal from M_1. P_7: volume control for loudspeakers L_{1c}. P_8: volume control for loudspeakers L_{1d}. P_9: ambiophony volume control, associated with M_2 and L_2. P_{10},P_{11}: volume controls for monitoring system and induction loop. *R*: delay wheel. S_1: selector for a second tape-recorder. S_2: direct/delayed sound switch for L_2. S_3 switch in feedback path of delay equipment. S_4: keys on stage manager's desk. *T*: tape-recorder.

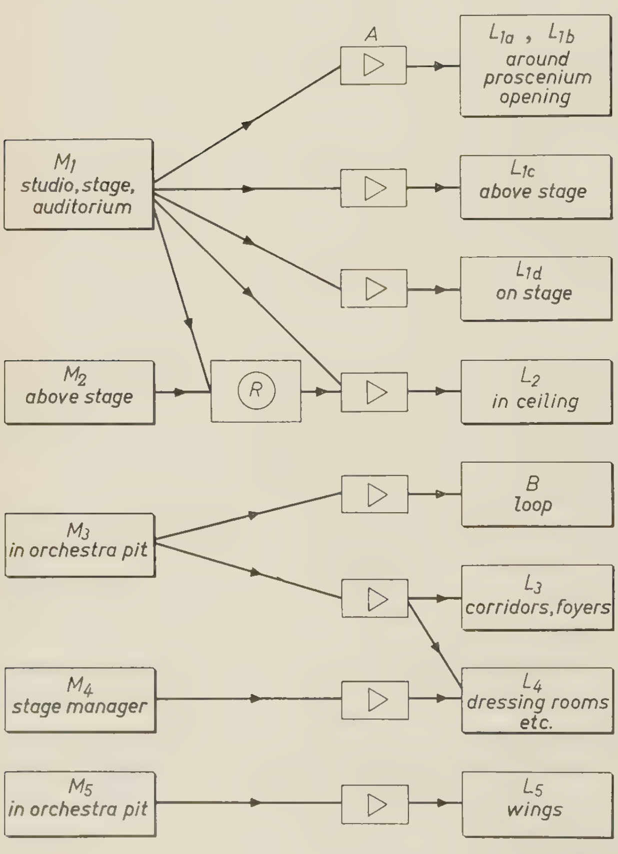


Fig. 12. Diagram to show how microphones, delay equipment, amplifiers and loudspeakers can be combined in the Scala. The letters have the same meanings as in fig. 11.

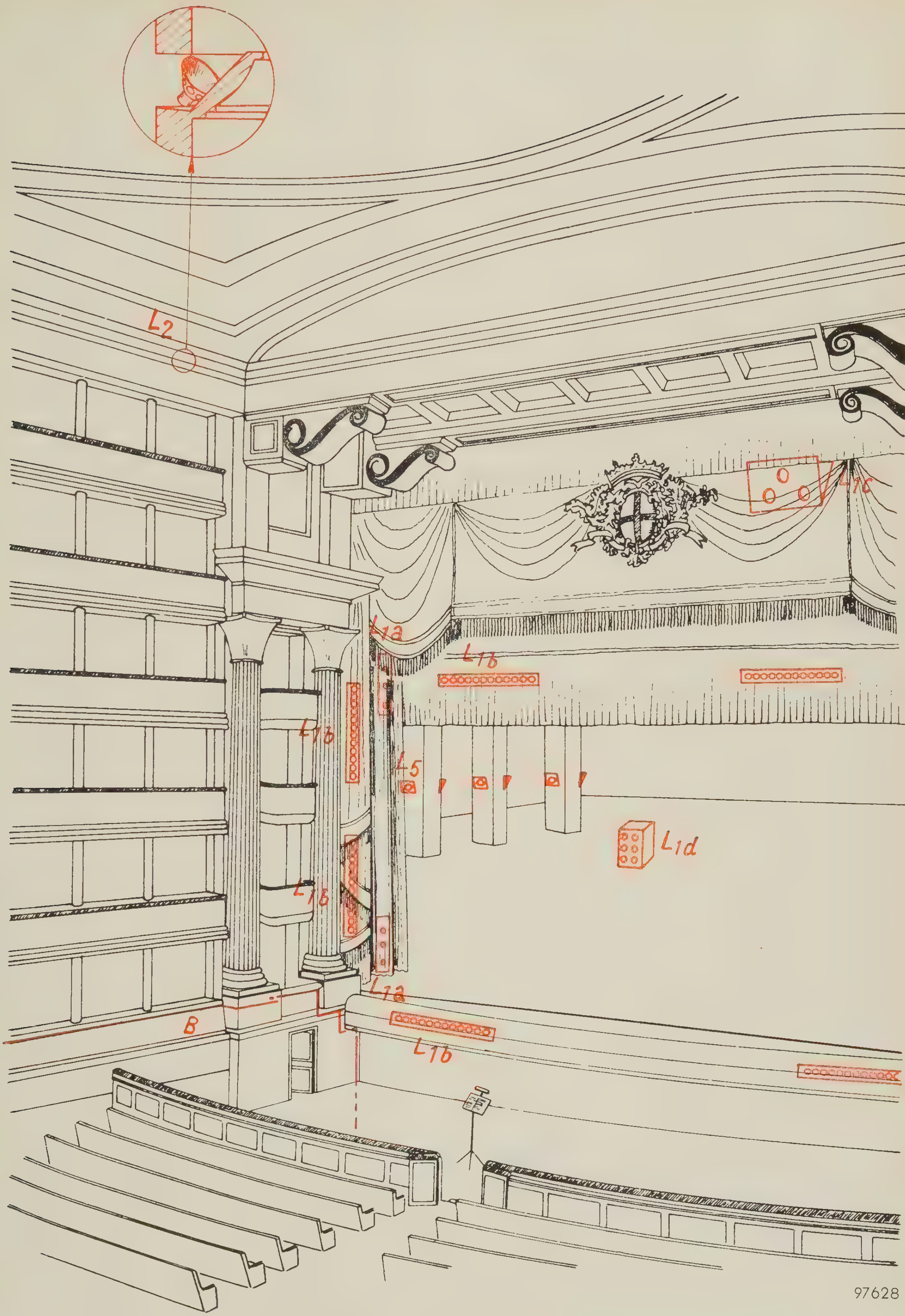


Fig. 13. Location of loudspeakers in the large auditorium of the Scala. L_{1a} are low-note boxes and L_{1b} loudspeaker columns mounted around the proscenium opening and providing panoramic sound. Placed above the stage, loudspeakers L_{1c} are used for overhead sound effects. Loudspeaker unit L_{1d} can be moved about the stage. Loudspeakers L_2 are mounted in the cornice and are responsible for ambiophony. L_5: loudspeakers for the benefit of actors awaiting their cues in the wings. B: induction loop of hearing-aid installation.

The control room also houses an ambiophony installation R (with microphones M_2), 18 power amplifiers (not including standby amplifiers) each of which has a power output of 120 W, and a number of monitoring loudspeakers.

The control room is linked to the sound *régisseur* and the studio by an intercommunications system. Musicians in the studio are able to follow the stage performance via loudspeakers connected to the monitoring system. The loudspeakers in the studio are put out of circuit whenever the microphones are switched on. Red pilot lamps in the studio and the control room and near the conductor and sound *régisseur* indicate that the microphones in the studio have been switched on.

Correction desk. The lighting and sound *régisseur* is responsible for lighting and electro-acoustic matters during the performance. His post is behind the Presidential box, where he sits at the correction desk referred to above; the desk enables him to correct the volume levels to which input channels M_1, T and G (fig. 11) have been adjusted, and to switch off the various groups of loudspeakers by means of relays.

Loudspeakers in the auditorium and on stage. The positioning of the various loudspeakers in the auditorium and on stage may be seen from *fig. 13*. A horizontal and a vertical loudspeaker column L_{1b} are placed in each of the four corners of the proscenium arch; associated with each pair of columns is a loudspeaker box L_{1a} for low notes. Individual loudspeakers belonging to the columns L_{1b} are aimed in directions such as will result in the high notes being distributed as evenly as possible. In combination, the loudspeakers of each pair of columns cover every seat in the house. The high-note loudspeakers (i.e. the columns) and the low-note loudspeakers are driven from separate power amplifiers. (This is the "Bi-Ampli" system [10])). The amplifiers are connected to separate output channels of the central control desk (fig. 11). The desk is provided with a control P_3 for adjusting the overall volume from all four loudspeaker groups. There are two further controls, P_4 and P_5, which, without altering the overall volume, govern the balance between the upper and lower groups and that between the left-hand and right-hand groups. It is possible by means of controls P_4 and P_5 to shift the stereophonic sound image vertically and horizontally through the proscenium arch.

Loudspeakers L_2 are fixed in a cornice running around the ceiling of the auditorium (fig. 13). These give diffuse sound, and can be used in two different ways. When they are connected up as a group the sound from them, though diffuse, clearly comes from above; this may be useful for certain effects. Connected to the four channels of the ambiophony installation, the loudspeakers can be made to simulate desired acoustic properties and to give the impression of a hall of any desired size; further, if their volume is given the right relationship to that from loudspeakers L_{1a} and L_{1b}, or the loudspeakers L_{1d} located on the stage, a certain impression of remoteness can be created. In either case a special effect can be obtained by using only those loudspeakers of the L_2 group that are situated at the back of the auditorium. It is possible thus to suggest sound echoing back from mountains, for example, or to bring about an interplay of sound with the stage (panoramic sound).

A control P_9 on the central control desk (fig. 11) enables reverberation to be added to the sound which is coming form the stage and being picked up by microphones M_2 above it. Control P_6 adds reverberation to sound coming from the studio or from recordings.

The loudspeakers L_{1d} just referred to as being on the stage (fig. 13) are mounted in groups on trolleys, each group having an output of 60 W. Their purpose is to reproduce instrumental and choral music and sound effects and the like from some point in the wings. Finally, L_{1c} is a loudspeaker group above the stage, whose function is to reproduce overhead sound effects — storms, rain, choirs of angels and the like. The volume controls for L_{1c} and L_{1d}, P_7 and P_8 respectively (fig. 11), are on the central control desk.

All the loudspeakers in the auditorium are of the double-cone EL 7021 type. The group around the ceiling and each of the four groups inside the proscenium arch are capable of producing, without perceptible distortion, a loudness level of 94 phons in the auditorium. This means that the music of a large orchestra or choir can be reproduced at the natural loudness level.

Monitoring and paging system; induction loop

The signal for the monitoring system is derived from four microphones M_3 (fig. 11) which, together, give an overall impression of the performance. One is placed behind the hangings above the proscenium, two in the orchestra pit and one in the chandelier high up in the auditorium. The signals from these microphones are mixed on a separate panel on hte

[10]) The advantages of reproducing low and high notes via separate channels have been described by G. J. Bleeksma and J. J. Schurink, A loudspeaker installation for high-fidelity reproduction in the home, Philips tech. Rev. 18, 304-315, 1956/57, and in particular p. 304 and p. 311 et seq.

central control desk, and are reproduced through the loudspeakers of groups L_3 and L_4 in the sound control room, in the 60 dressing rooms, in the foyers (for the benefit of latecomers), in the offices of the management and in the studio.

Behind the stage the stage manager has his own control desk (fig. 4) with a microphone M_4 and amplifier (figs. 11 and 12). By manipulating the keys S_4 of this desk he is able to call up individual artistes or groups of artistes via the loudspeakers of the monitoring circuit.

For the convenience of artistes awaiting their cues in the wings, loudspeakers L_5 have been suspended from the pillars on either side of the stage (fig. 13). The signal for these is derived from two microphones M_5 (fig. 11) in the orchestra pit; it passes through an amplifier with a compressor circuit, which obviates overloading during fortissimo passages, though solos and pianissimi remain quite audible.

An induction loop is laid round the auditorium (B in figs. 11 and 13) for the benefit of the hard of hearing. The signal is derived from M_3, the microphones feeding the monitoring circuit, and passes through a 120 W amplifier. Hearing-aids are hired out by the theatre.

Théâtre National Populaire (Palais de Chaillot), Paris

The Palais de Chaillot was built for the World Fair held at Paris in 1937, and occupies the site of the old Trocadero. It consists of a combined theatre and concert hall seating 2900, part of which is built into rising ground, and of two wings which lie at a higher level and which are used as museums. In front of the stage is a spacious orchestra pit. The rear wall of the stage is entirely occupied by a large organ. The theatre is used for stage performances (mainly given by the Théâtre National Populaire company under Jean Vilar), symphony concerts, organ recitals, film shows and galas (shows of various kinds to which admission is by invitation only); on more than one occasion the theatre has served as a congress hall for the United Nations.

The reverberation time is on the short side for music, but for speech it is so long that intelligibility suffers. Many of the seats are so far from the stage that intelligibility is definitely poor.

The existing electro-acoustical installation was built on the initiative of the technical management of the Théâtre National Populaire, who were conscious of the need to settle the intelligibility problem once and for all, numerous experiments having yielded no solution. The decision in regard to the equipment to be used was certainly not unconnected with the success of the "Spectacles Son et Lumière", for which numerous French châteaux and other historical buildings had been provided with electro-acoustical installations.

In the Théâtre National Populaire, unlike the Scala, the emphasis lies on improving intelligibility. The preference for recorded music reproduced stereophonically on the stage, instead of live music relayed from a studio, constitutes a second difference. The arrangements for recording sound are accordingly more elaborate than those at the Scala. Provision has also been made for improving the acoustics of the theatre when symphonic concerts and organ recitals are given. Something has already been said about the sound and television links to the foyer, intended for latecomers, as also about the paging system used to announce the end of the interval and the like, to members of the public gathered in foyers and corridors and on staircases etc. In addition to this, there is an monitoring system for actors in their dressing rooms and for members of the technical staff, the latter being in touch via an intercommunications system.

Despite the above differences in the emphasis laid on various aspects of the installation, in the technical sense it bears a strong resemblance to that in the Scala. The heart of the Chaillot installation is the acoustic control room housing the central control desk (fig. 8). But for a few points of detail, the control room is similar to that in the Scala. One difference is that the Chaillot installation allows for stereophonic reproduction of direct sound; there are two quite separate channels for the loudspeakers beside the stage, and two further separate channels for the loudspeakers on the stage. Moreover, the loudspeakers around the auditorium can be used to create moving and panoramic sound images. The presence in the Palais de Chaillot of a special recording desk is evidence of the prominent place given to recorded sound. The desk incorporates two tape-recorders for recording and playing back, and two gramophones, all of professional type. Because two tape-recorders are available, it is possible not only to give a continuous programme of recordings, but also to make copies on the spot, and to produce special effects by transposing speeds (as is done by composers of electronic music [11])) and in other ways.

Microphone positioning

25 microphone points are provided for the stage. The sound *régisseur* is free to decide on the layout of

[11]) H. Badings and J. W. de Bruyn, Electronic music, Philips tech. Rev. **19**, 191-201, 1957/58.

microphones in the orchestra pit, for the organ, and on the stage during galas. There is little danger of acoustic feedback from microphones employed thus, but stage performances are another matter. Microphone positioning then becomes much more difficult. The microphones must be placed unobtrusively, they must not interfere with stage action and scene-changing, nor must they pick up any extraneous noise from behind the scenes. In many respects the best place is in the footlights, where the microphones can catch high frequencies in the speech of actors facing the auditorium, as is needful for proper intelligibility. The difficulty is that the microphones have to pick up sound from the whole of the stage (which is 50 feet deep and up to 75 feet wide!); at the same time the position in the footlights is an extremely bad one from the viewpoint of acoustic feedback, for the microphones are right in front of the loudspeakers which stand on either side of the stage and which have to render the sound intelligible at the back of the 40 m long auditorium. Clearly, the problem of acoustic feedback dominates everything else here. Indeed, the best possible arrangement of the microphones was only discovered after a great deal of trial and error. Now the microphones are always set up in the same places and their signals are always combined in the same way.

Four small columns, each containing four electrodynamic type EL 6040 microphones, are placed in the footlights. The columns are in symmetrical pairs to the left and right of the centre of the stage. The left-hand pair feeds a loudspeaker column on the left of the stage, the right-hand pair a loudspeaker column on the right of the stage, this providing a stereophonic effect. With this installation intelligibility is good throughout the auditorium, there are no unwanted echoes, and the audience are not conscious of the fact that any of the sound is coming from the loudspeakers.

Stereophonic recordings

Stereophonic recordings of music on the stage are made with the aid of an artificial head. There is usually no audience on these occasions, and the appearance of the head would not have mattered were it not for the fact that it is occasionally desired to make recordings (of a documentary nature, for example) in the presence of the public. The artificial head had therefore to be as inconspicuous as possible, and accordingly it was made in the form of a transparent plate with a slim microphone of type EL 6040 on either side. Part of the plate can pivot in its own plane, allowing large or small differences to be introduced into the path lengths to the two microphones; these differences correspond to stereophonically-effective field angles [12]) of 90° and 180°. The pivoting portion is adjusted to the angle that gives a stereophonic sound image corresponding as closely as possible to the configuration of the various musical instruments during the recording. For recording a large orchestra or a stage performance, the artificial head is suspended in front of the stage; for recording stereophonic sound effects or the music of a small ensemble, the head is mounted on a stand and placed on the stage.

The auditorium and stage loudspeakers

The total of 129 loudspeakers employed for improving the acoustics of the theatre can be divided into three groups according to location, namely (*a*) around the proscenium arch, (*b*) on the stage, and (*c*) around the ceiling.

(*a*) *The loudspeakers around the proscenium arch* are in two symmetrical groups to left and right of the centre of the stage. Each group comprises a vertical column beside the proscenium arch, a horizontal column placed at the top (see figs. 11 and 12 of Part I) and a box for low notes. The left-hand and right-hand groups are connected to separate output channels of the central control desk.

Each of the *vertical columns* comprises 18 double-cone loudspeakers of type EL 7021, which reproduce frequencies above 250 c/s. They are inconspicuously housed in small cabinets aimed towards the audience, so as to provide direct sound. Successive loudspeakers forming a column are mounted at slightly different angles so that, in combination, they cover the whole of the auditorium. This results in even diffusion of the high notes (see Part I, p. 319) and makes the radiating angle of the columns almost independent of frequency.

Each of the *horizontal columns* comprises ten loudspeakers of type EL 7021, housed similarly in small cabinets. The angles at which they are mounted are also staggered, but they are pointed towards the ceiling and the walls, not towards the audience. In this way maximum diffusion is achieved.

Each of the *low-note boxes* contains two EL 7031 high efficiency (14%) loudspeakers that reproduce frequencies below 250 c/s. The cubic capacity of the boxes is large enough to allow them to reproduce the lowest musical notes of all. They are mounted near the ceiling, above the vertical columns.

The central control desk enables the above groups of loudspeakers to be operated in the following five ways:

---

[12]) Philips tech. Rev. **17**, 174 (fig. 5), 1955/56.

(1) the vertical columns only, for speech;
(2) the vertical columns combined with the low-note boxes, for music (direct sound);
(3) the horizontal columns only, for diffuse sound from above the stage;
(4) the horizontal columns combined with the low-note boxes, for music (diffuse sound);
(5) all groups together, for the optimum reproduction of music.

The optimum relationship between the sound volumes given by the vertical and horizontal columns and the low-note boxes was established from comprehensive listening tests.

During stage performances at the Théâtre National Populaire the spoken word is supported stereophonically via the microphones in the footlights and the vertical loudspeaker columns. Stereophonic recordings of music and sound effects are reproduced by one of the five loudspeaker combinations listed above.

(*b*) *The loudspeakers on the stage* are housed in large cabinets; each cabinet contains one EL 7031 and four EL 7021 loudspeakers, the combined output being 60 W. Their function is to reproduce music and sound effects from the wings during stage performances. They can be connected to two separate output channels of the central control desk, and it is therefore possible to arrange for two different sounds to come simultaneously from different directions, or to achieve stereophonic reproduction either in breadth or in depth. Combined with the horizontal columns, the stage loudspeakers can be made to create a panoramic effect whereby the sound appears to travel around the proscenium arch; by combining them with the vertical columns it is possible to move the sound image up and down stage.

(*c*) *The loudspeakers around the ceiling* are of type EL 7021 and are housed in shallow cabinets aimed obliquely upwards, so that they give diffuse sound. Diffuse reverberation can be produced by conferring suitable delays on the signals to these loudspeakers; an EL 6910 ambiophony installation embodying a magnetic delay wheel (see figs. 22 and 23 in Part I) is employed for this purpose. In principle, the ceiling loudspeakers are apportioned amongst the four delayed-signal channels on a random basis, but care is nevertheless taken to see that no speaker is given a delay less than that consonant with its distance from the stage when the delay wheel has a peripheral speed of 3 m/s. If the speed is reduced to 1.5 m/s all the delay times are doubled, and the auditory impression is that of a hall of very great size. The central control desk has facilities for giving reverberation times between 0 and 4 sec to the sound from the ceiling loudspeakers.

During concerts the signal for the ceiling loudspeakers is derived from microphones above the orchestra or at the organ; during stage shows and galas the ceiling loudspeakers are supplied from microphones in the footlights or on the stage, or from tape-recordings or gramophone records. These loudspeakers can be combined with the stereophonic groups, or with the large units on the stage, in order to produce distant-sound effects.

The earlier-mentioned random distribution of the ceiling loudspeakers amongst the four delay channels — necessary for ambiophony — is obtained only when a certain switch on the central control desk is in the "reverberation" position. When the switch is put into the other position, marked "panorama", relays come into action and modify this random distribution, connecting each of the four amplifier outputs to a group of loudspeakers occupying one quadrant of the ceiling. At the same time other relays bring a "panorama potentiometer" into circuit; this device, which is also housed in the central control desk, now controls the inputs of the four amplifiers. The signals to the ceiling loudspeakers are no longer being delayed, and consequently the sound from these speakers gives an impression of direction that depends on the proportions in which the four quadrant groups are contributing to the overall volume. The panoramic potentiometer enables these proportions to be varied, and in consequence the apparent direction of the sound to be altered. Very striking sound effects can be produced in this way. The signal for panoramic sound is of course derived from a recording.

As an illustration of the scale of the "service" installations (monitoring, paging and intercommunications), it may be noted that they involve the use of 355 loudspeakers outside the auditorium.

Grand Auditorium at the 1958 Brussels World Fair

For the purposes of the international exhibition held in Brussels in 1958, one of the "palaces" that had survived from the 1935 World Fair was converted into a large hall (fig. 1 — in the meantime it has been demolished). The hall seated 2300 persons and was used for the many shows and gatherings already mentioned (p. 53).

The hall had a cubic capacity of 15 000 m^3, its walls were covered with a material that was highly sound-absorbent, and the lighting arrangements required that it should have a perforated ceiling. All this resulted in a reverberation time (1.4 sec at 500 c/s in the empty hall) that was far too short for music. The acoustics were not unfavourable to

speech, but intelligibility left much to be desired at the back of the hall, owing to its great length (45 m).

Intelligibility

Intelligibility was improved by means of the stereophonic support afforded by 2×2 microphones on the edge of the stage and loudspeaker columns on either side of the proscenium arch (fig. 1). It was impossible for architectural reasons to give individual loudspeakers directions such that the high frequencies would be evenly distributed throughout the hall. Moreover, it was found that, in some parts of the hall, the position of the stereophonic image varied according to the seat occupied. These difficulties were overcome by placing small loudspeaker columns behind the hangings above the stage, giving them suitable angles and connecting them in parallel with the vertical columns.

As was shown in Part I (p. 319), it is desirable to attenuate the low frequencies in speech; this was achieved with the aid of a high-pass filter with a 250 c/s cut-off.

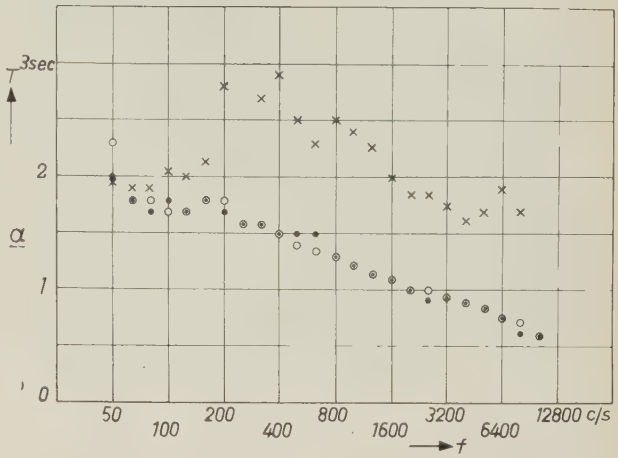
Music from the orchestra pit

The same stereophonic installation, but with 2×2 microphones placed in the orchestra pit, served for supporting the music played in the pit, insofar at least as frequencies above 250 c/s were concerned. For reproducing the range below 250 c/s, low-note loudspeakers, placed beside each of the vertical columns, were switched in via the central control desk; further there was a choice between low and high positioned groups for the low notes. The low-note loudspeakers were driven via a low-pass filter with a 250 c/s cut-off.

This installation was also used for backing up singing on the stage and the quieter instruments played there.

Acoustics for music

The points and circles plotted in *fig. 14a* indicate values of the reverberation time T measured by the Technical-Physics Service of the T.N.O. (Applied Physics Research Institute) and the Technische Hogeschool Delft with the ambiophony installation out of action; see also curve *1* in fig. 14*b*. The reverberation time T was 1.4 sec at 500 c/s and 0.6 sec at 10 000 c/s. In a hall with a cubic capacity of 15 000 m^3, these values should be about 2 sec and 1.0 sec if the acoustics for music are to be good. After final adjustments of the ambiophony installation and application of a correction for the low-notes, T varies approximately according to curve *2* with the reverberation knob turned up to the maximum extent, and according to curve *3* with the knob in a central position. The knob was placed in a central position for most of the musical programmes, with very satisfactory results.



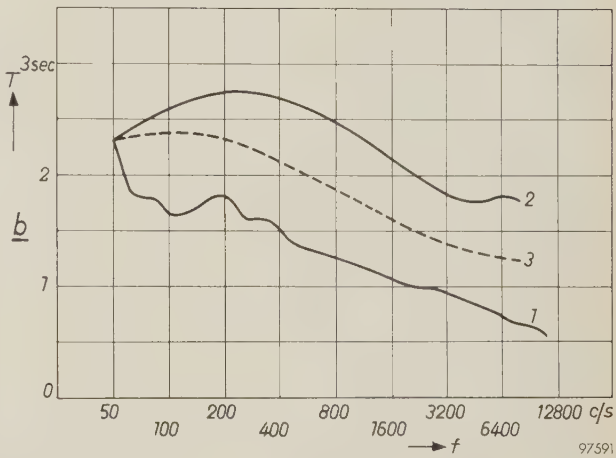


Fig. 14. Reverberation time T as a function of frequency. The diagrams relate to the Grand Auditorium at the 1958 Brussels Exhibition, with no audience present and the curtains drawn.
(*a*) Values measured by members of the Technical-Physics Service T.N.O.-T.H., Delft. The points and circles represent values measured with a microphone in the front and rear of the auditorium respectively, and with the ambiophony installation out of action. The crosses relate to provisional measurements carried out with the ambiophony installation giving maximum reverberation, but before final adjustments had been made to it.
(*b*) Curve *1* is drawn through the points and circles in *a*. Curves *2* and *3* were derived by the author after the ambiophony installation had been finally adjusted and correction had been made for low frequencies. Curve *2* represents T as a function of frequency f when the reverberation control was turned up to the maximum, and curve *3* is appropriate to the central position in which the control was placed for most of the musical performances.

Broadcasts

A very large number of the events taking place in the Grand Auditorium were broadcast. The existing microphones of the installation were employed for this purpose. All these microphones were of the condenser type, that type having been chosen with

the requirements of radio broadcasting in mind. The condenser microphone is remarkable for having a very flat response curve that extends from the lowest to the highest sound frequencies. The directivity pattern of EL 6051, the type with which the hall was equipped, can be changed by switching; the directional characteristic can be either omnidirectional or cardioid. (cf. Part I, p. 326).

The positioning of microphones for improving the acoustics of the hall was based as far as possible on the layouts required by the broadcasting engineers. Signals for the broadcasting desk were derived from the six microphone channels on the central control desk (tapped from points *before* the controls, to permit separate adjustment of the sound in the hall and the broadcast signal).

In some cases layouts other than the broadcasting ones were considered desirable from the viewpoint of auditorium acoustics. It happened in this way that on occasion more than six microphones were needed at a time. This situation called for an extra control desk allowing six microphones, whose signals could be adjusted separately, to be connected up to *one* input of the broadcasting desk. Thus the broadcasting engineers had a total of eleven microphone channels at their disposal. Electrically generated reverberation was available for mixing into the radio signal.

Radio commentators had the use of four booths with a view of the hall.

Other facilities

The other facilities can be dealt with very briefly. Much importance was attached to the recording of performances and the reproduction of recordings on tape or discs. Accordingly, special desks were available for gramophone reproduction and for stereophonic recording and reproduction using magnetic tape, the former desk embodying two professional gramophones and the latter two professional tape-recorders. It was possible to blend electrically-generated reverberation into the recordings, the central control desk being employed as a mixing desk.

Most performances in the Grand Auditorium were given once only. Rehearsals were therefore the exception rather than the rule, and they were always limited, so there could be no question of carefully preparing the sound effects. Accordingly, no arrangements were made for providing panoramic sound, as available in the Scala and the Chaillot theatres. Even so, certain sound effects over and above stereophony and ambiophony were available with the installation as it stood. By cutting out the filter for the low-note speakers referred to above, and using each of them separately to reproduce the whole audible range, it was possible to cause sound to come from left or right or from above or below: operated in conjunction, these speakers could be made to suggest a sound source moving horizontally or vertically.

The "wireless" installation for simultaneous interpreting, with its six interpreter's cabins and six channels, has already been discussed (figs. 5 and 6). Mention may also be made of the loop installation for the hard of hearing and of the general monitoring system for artistes in their dressing rooms, technical personnel and members of the public in foyers.

Gebouw voor Kunsten en Wetenschappen in The Hague

Dating from 1874, the Gebouw voor Kunsten en Wetenschappen (Arts and Sciences Building) contains a hall seating 2100 and having three balconies. The hall is mainly used for concerts, but in addition plays and shows are given and big meetings are held there. It has possessed an ambiophony installation since 1954. Apart from the Philips theatre in Eindhoven, this was the first building to be provided with such an installation [13]). Experience gained here has contributed a great deal to the success of the installations built in other countries and described above [14]).

In October 1958 the old installation made way for a new one. The reasons for the change were (1) it was desirable to replace the prototype ambiophony installation by the definitive version of the equipment; (2) the large loudspeakers mounted along the parapet of one balcony were unsightly; and (3) further steps had to be taken to improve intelligibility and to "bring out" the organ, which was badly sited in the acoustical sense.

Here we shall do no more than touch upon a few particular aspects of the new installation.

Loudspeakers for ambiophony

The old ambiophony installation comprised 54 loudspeakers mounted in the rear of the hall and in the back walls of the first and second balconies, and six large boxes fixed to the parapet of the second balcony. The latter were so bulky and conspicuous that it was felt that they should not figure in the final

13) See figs. 3, 5 and 8 and p. 265 of the article cited in [4]).
14) We should like to take this opportunity of expressing our appreciation for the interest and cooperative spirit that the management of the Gebouw voor Kunsten en Wetenschappen have always shown in connection with experiments in this new field of acoustical engineering.

installation. Necessarily bulky, because good low-note reproduction requires a large enclosed volume of air behind the cone, these loudspeakers could not be rendered inconspicuous except by mounting them high up in the side walls of the hall, immediately under the ceiling. But this positioning would have defeated the main aim in view, in that the high notes would not have penetrated sufficiently far into the hall and there would have been places where the sound was not diffuse enough.

We therefore adopted a quite different approach, based on the fact pointed out in Part I that it is impossible to tell the direction from which low-pitched sounds are coming. The following solution was settled on. To augment the sound from the 54 loudspeakers referred to, which reproduce both high and low frequencies, eight large loudspeakers handling low frequencies only were mounted in the side walls just under the ceiling. High frequencies are reproduced by a total of 106 loudspeakers in small cabinets scattered over the walls. 52 of these are inconspicuously mounted beneath the first balcony and along the lower edges of that and the second balcony (*fig. 15*). The cones of the loudspeakers along the balconies are inclined downwards, giving coverage to the stalls. In spite of being angled on to the arena of the hall, these loudspeakers produce diffuse sound in virtue of their large number and their random distribution amongst the four delayed-signal channels of the EL 6910 ambiophony installation. The cabinets are open at the back, so that sound radiated to the rear contributes to reverberation on and below the first balcony. The four delayed-signal channels drive the low-note and high-note loudspeakers via filters with a cross-over frequency of 250 c/s.

16 high-note loudspeakers in small cabinets are mounted underneath the first balcony, 16 on that balcony, 12 on the second balcony and 10 on the third one. Besides forming part of the ambiophony arrangements, these loudspeakers have an important function in the installation for improving intelligibility, which we shall now go on to discuss.

Improving intelligibility

Earlier on, intelligibility was poor (1) at the back of the hall where the first balcony is too low above the heads of the audience (the sound arriving here has undergone excessive attenuation caused by the audience in front), (2) on the third balcony, where the ratio of direct to reverberating sound is too low on account of the distance from the stage, and (3) in many other places on those occasions when there is a great deal of audience noise (at revues and the like).

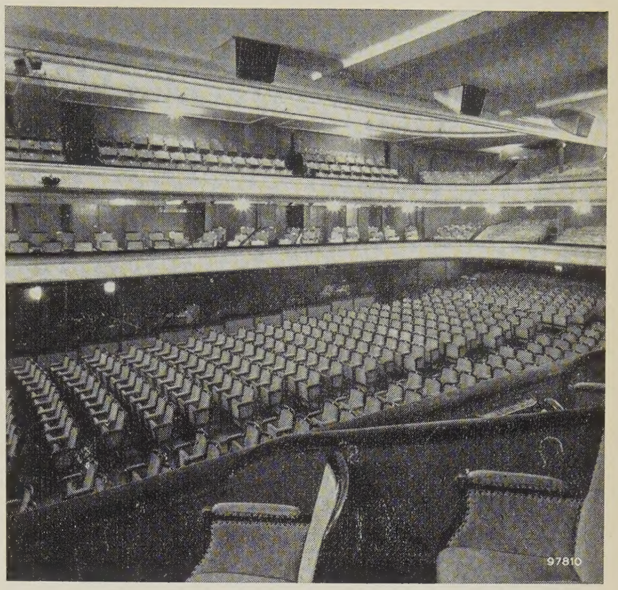


Fig. 15. Auditorium of the Gebouw voor Kunsten en Wetenschappen in The Hague, viewed from a box on the first balcony. Three of the small loudspeakers may be seen along the lower edge of the second balcony.

To improve intelligibility, four loudspeaker columns are mounted on either side of the front part of the auditorium, one pair at head height below the first balcony, another pair above that balcony, another above the second and another above the third balconies. These columns, each of which contains five EL 7021 loudspeakers, give coverage to the stalls and to side and rear balcony seats. However, sound from the columns is no better able than voices from the stage to penetrate the deep space under the first, overhanging, balcony. To reach seats here, the loudspeaker signal would have to be amplified so much that the volume would be excessive for members of the audience seated nearer to the columns, and there would be a risk of acoustic feedback into the microphones on the stage.

This being so, it was decided to make use of the delay equipment and supply the back stalls, via loudspeakers in the rear of the hall, with sound arriving about 10 milliseconds later than the sound from the stage and the columns. The impression given is that of sound coming from the stage. Only when one is closer than half a metre to the loudspeakers beneath the balcony is one conscious of the fact that sound is coming from them; however, they are mounted a good metre away from the nearest seats.

The same method has been employed to improve intelligibility in the back seats of the first, second and third balconies.

Thus the delay equipment can be operated in two ways:

(1) to produce an ambiophonic effect; all the loudspeakers around the auditorium (except those of the third balcony) are distributed amongst the four channels and the feedback is put into action;
(2) for making speech more intelligible: only the $16 + 16 + 12 + 10$ loudspeakers referred to above are operative, being supplied from one of the delayed signal channels; the feedback is switched off.

Operation

First and foremost, the new installation had to be simple to operate; a second requirement was that it should be possible to make readjustments from one given place in the hall.

The first requirement was met by abandoning the idea of a large central control desk, the amplifier rack merely being provided with four switches marked "stage", "soloist", "orchestra" and "organ". Each switch brings into action a set of microphones appropriate to the type of performance indicated: the pre-amplifiers associated with the microphones are automatically switched on and their outputs connected to certain power amplifiers or to the ambiophony installation, the signals passing through attenuators that have been adjusted once and for all on the basis of listening tests. Switching is also possible for combinations such as orchestra and soloist, orchestra and organ, and stage with commentator (as in Arthur Miller's play "A view from the bridge").

The switch marked "stage" brings into action four EL 6031 microphones (*fig. 16*) mounted along the edge of the stage. The loudspeaker columns also come into action, and relays switch the delay equipment over to "speech" irrespective of whether other switches are on or not. In all other cases the delay equipment functions as part of the ambiophony installation. The switch marked "soloist" puts the soloist's microphone into operation, together with the columns and the ambiophony installation; the ratio between the intensities of the direct and indirect sound is adjusted in advance. The "orchestra" switch brings in the ambiophony installation only, the signals being derived from microphones above the podium. The "organ" switch links the organ microphone to the columns (which "put the organ on stage" acoustically) and to the ambiophony installation, which adapts the acoustics of the hall to organ music; in addition, low organ notes are backed up by loudspeakers in the ceiling.

The requirement that correction should be possible from some point within the hall has been met by providing a small mobile correction desk. Remote control is achieved very simply by making use of the new cadmium-sulphide photo-resistors [15]). Inserted in series with the volume controls on the amplifier rack, the CdS resistors are exposed to the light from small electric bulbs. The (direct) current flowing through each bulb can be controlled with the aid of a rheostat on the correction desk. The resistance of the cadmium sulphide, and hence the signal strength, varies with the luminous flux from the bulb. The system is quite free from crackle and is cheaper than a system with conventional crackle-free potentiometers. A second advantage is that all the cables between the correction desk and the amplifier rack carry direct current. There was therefore no need for the long screened low-impedance cables that had to be used in the Scala.

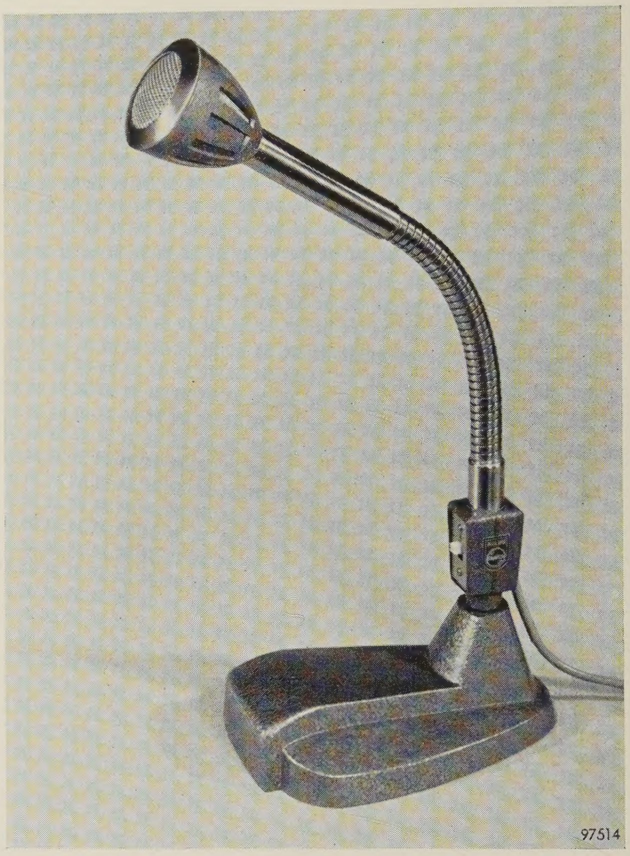


Fig. 16. Type EL 6031 electro-dynamic microphone on flexible mounting. The microphone has a hypercardioid directional characteristic.

It is possible from the correction desk to switch off various loudspeaker groups, singly or all together, by means of relays. Provided the "stage" switch is not on, it is also possible from this point to switch the delay equipment from "ambiophony" to "speech" and *vice versa;* one case in which this may be necessary is during operettas, when singing is interspersed with spoken passages.

[15]) N. A. de Gier, W. van Gool and J. G. van Santen, Philips tech. Rev. **20**, 277-287, 1958/59 (No. 10).

Volkswagen factory, Wolfsburg

We shall now leave the world of music and the theatre and give a short description of the unusual public-address installation in the Volkswagen factory.

It is laid down by law in the German Federal Republic that factory managements must call all employees together every three months and give them an account of the business and production situations. The Volkswagen factory employs about 35 000 people. The only meeting place capable of accommodating such a multitude is obviously the factory itself. Accordingly, the meetings are held in three or four adjacent aisles of the factory — *which* aisles are chosen depends on the circumstances at the time; alternatively, the meetings may take place in the open if the weather is good.

Each aisle is 250 m long, 25 m wide and only 8 m high. The roof rests upon heavy pillars spaced at intervals of 8 m and forming the divisions between the aisles. The surfaces of walls, roof, floor, pillars, machines etc. are very hard, acoustically, and do not by any means favour intelligibility. Equally unfavourable is the sawtooth shape of the roof, with its numerous, almost completely undamped, resonant cavities. Add to this the enormous length of the aisles (from the speaker to the furthest listener is about 200 m) and their lack of height, and it will be plain that achieving a fair degree of intelligibility was no easy problem. The problem was further complicated by the need for the electro-acoustical installation to be easy to set up and dismantle (this on account of the changing locale of the meetings), which meant that excessive decentralization had to be avoided; moreover, the installation had to ensure proper intelligibility in the open air as well as inside.

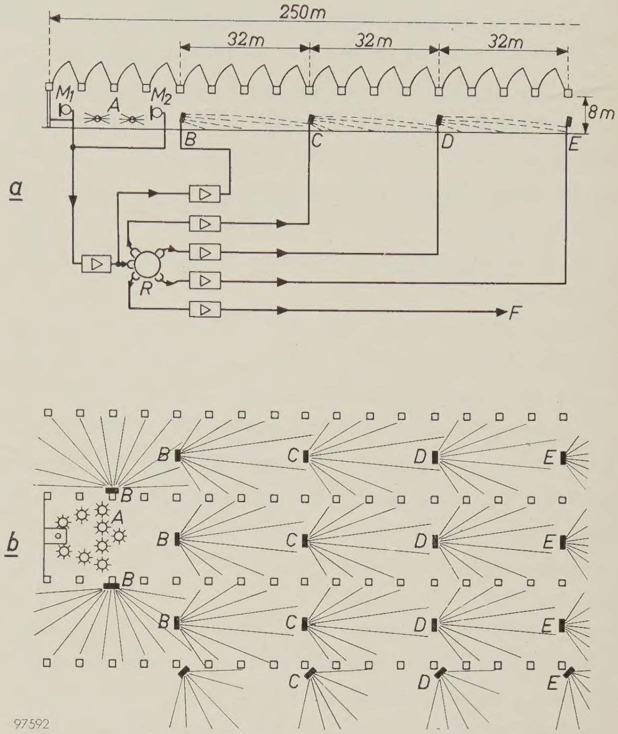


Fig. 17. *a*) Vertical section, and *b*) ground plan of a shop in the Volkswagen factory, where meetings attended by labour and management are held every three months. M_1, M_2: microphones. A: small loudspeakers with omnidirectional radiation pattern (see fig. 19). R: delay equipment supplying loudspeaker columns $B \dots F$ (C is delayed 0.1 s with respect to B, D is delayed 0.1 s with respect to C, and so on). The angles at which loudspeakers are mounted in their columns are staggered in such a way that sound is evenly distributed over the areas covered by the columns.

Fig. 18. Shop in Volkswagen factory during a works meeting. Some of the loudspeaker columns (C, D, E in fig. 17) may be seen in the photograph.

The design adopted was based on the principle illustrated in *fig. 17* (cf. fig. 17 of Part I). 32-metre sections of each aisle are supplied with sound from a loudspeaker column, the signal to each column being delayed by 0.1 s with respect to the signal fed to the column in front of it (this is roughly the time sound requires to travel 32 m). The columns have a slight forward tilt (fig. 17*a*), and the loudspeakers making up each column have a lateral skew such that they distribute sound evenly over the section of aisle to be covered (fig. 17*b*). *Fig. 18* is a photograph taken at one of the works meetings.

The above system has the advantage of giving hearers the impression that the sound is coming from the direction of the speaker. If it seemed to come from any other direction, their attention would soon start to wander, the tendency to embark on private conversations would increase, and the resulting increase in the noise level would mean decreased intelligibility, even less attention to the speaker, and so on.

A different solution has been adopted for the part of the factory (to the left in fig. 17) occupied by the speaker's chair and by tables at which members of the management and works council and representatives of the press are seated. Small loudspeakers with an all-round radiation pattern are set up on these tables (*fig. 19*). In view of the short range to the listener, the loudspeakers need only supply a small volume of sound. Consequently there is absolutely no danger of howl due to acoustic feedback.

The amplifiers and the delay equipment are mounted on a trolley in view of the desire for mobility. The setting up and dismantling of the whole installation do not take more than two or three hours.

Fig. 19. One of the small omnidirectional loudspeakers (*A* in fig. 17) that are placed on tables occupied by management, works council and press.

For open air meetings the loudspeaker columns are grouped together in larger units. The signals to all units are in phase, the delay equipment being put out of action by means of a switch. In this manner speech can be reproduced with proper intelligibility in the open air.

Summary. The most important acoustical problems arising in theatres are those relating to intelligibility, to the acoustics for music played in the orchestra pit or elsewhere, and to the acoustics as they affect the actors and musicians. Visual requirements are often found to conflict with acoustic ones. The latter can however be satisfied by taking suitable steps to support speech and music with direct and indirect sound from an electro-acoustical installation. Requiring no special staff to operate it, an installation of this kind enables theatre premises to be exploited in new ways.

Besides an installation having purely artistic functions theatres have need of electro-acoustical facilities of other kinds, such as a monitoring system for management and artistes, a paging system for communicating with artistes in their dressing rooms, technicians and members of the public, an installation for the hard of hearing, a simultaneous-interpreting installation for use at international congresses, and so on. Closed-circuit television has also proved of value; one of its uses is to make the orchestra conductor visible to musicians in a separate studio, and another is to allow latecomers to follow stage proceedings from a foyer.

The sound control room is the heart of the whole electro-acoustical complex. Having described the equipment to be found therein, the author deals with the large installations that have been built in the Scala in Milan, the Théâtre National Populaire (Palais de Chaillot) in Paris, the Grand Auditorium at the 1958 Brussels World Fair, the Gebouw voor Kunsten en Wetenschappen in the Hague and the Volkswagen factory at Wolfsburg.